ENGINEERING AND EXPEDITIONARY WARFARE CENTER

**TECHNICAL REPORT**
**TR-NAVFAC-EXWC-EV-1706**
**DECEMBER 2016**

# Final Report : Innovative Acoustic Sensor Technologies for Leak Detection in Challenging Pipe Types

Gary Anguiano, NAVFAC EXWC
Edwin Chiang, NAVFAC EXWC
Martha Araujo, NAVFAC EXWC
Stuart Strum, NAVFAC EXWC
Dr. Victor Medina, USACE ERDC
Scott Waisner, USACE ERDC
Wendy Condit, Battelle
Dr. John Matthews, Battelle
Ryan Stowe, Battelle

This page is intentionally left blank.

# REPORT DOCUMENTATION PAGE (SF 298)

*Form Approved*
***OMB No. 0704-0811***



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From – To)* |
|---|---|---|
| 30-12-2016 | Technical Report | Mar 2013 –Dec 2016 |

**4. TITLE AND SUBTITLE**

FINAL REPORT: INNOVATIVE ACOUSTIC SENSOR TECHNOLOGIES FOR LEAK DETECTION IN CHALLENGING PIPE TYPES

**5a. CONTRACT NUMBER**

N3943013C1256

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

6. AUTHOR(S)

Gary Anguiano; Edwin Chiang; Martha Araujo; and Stuart Strum (NAVFAC EXWC)
Dr. Victor Medina; and Scott Waisner (USACE ERDC)
Wendy Condit; Dr. John Matthews; and Ryan Stowe (Battelle)

**5d. PROJECT NUMBER**

1309665

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES**

1000 23rd Ave
Port Hueneme, CA 93041

**8. PERFORMING ORGANIZATION REPORT NUMBER**

TR-NAVFAC-EXWC-EV-1706

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 17D08,
Alexandria, VA 22350-3605

**10. SPONSOR/MONITORS ACRONYM(S)**

ESTCP

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

EW-201339

**12. DISTRIBUTION/AVAILABILITY STATEMENT**

Unlimited

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**

Reducing water loss at U.S. Department of Defense (DoD) installations is important to preserve potable water needed for essential functions and to limit the drawdown of local water supplies. Implementation of improved leak detection technologies and the timely repair of water mains will support Federal and DoD sustainability goals. This project assessed three innovative acoustic leak detection technologies with enhanced cross-correlation features to detect and pinpoint leaks in challenging pipe types, as well as metallic pipes.

**15. SUBJECT TERMS**

Leak detection; acoustic correlation; water distribution systems

| 16. SECURITY CLASSIFICATION OF: a. REPORT | b. ABSTRACT | c. THIS PAGE | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| U | U | U | UU | 109 | Gary Anguiano |
| | | | | | 19b. TELEPHONE NUMBER *(include area code)* (805) 982-1302 |

## Disclaimer

This publication is intended to be informational and does not indicate endorsement of a particular product(s) or technology by the Department of Defense or NAVFAC, nor should the contents be construed as reflecting the official policy or position of any of those Agencies. Mention of specific product names, vendors or source of information, trademarks, or manufacturers is for informational purposes only and does not constitute or imply an endorsement, recommendation, or favoring by the Department of Defense or NAVFAC. Although every attempt is made to provide reliable and accurate information, the authors of this publication do not warrant or otherwise represent in any way the accuracy, adequacy, efficiency, or applicability of any product or technology discussed or mentioned herein, including the suitability of any product or technology for a particular purpose.

# Table of Contents

## List of Figures

## List of Tables

# Appendices

# Abbreviations and Acronyms

| | |
|---|---|
| AC | asbestos cement |
| AMI | advanced metering infrastructure |
| AWE | Alliance for Water Efficiency |
| AWWA | American Water Works Association |
| | |
| CERL | Construction Engineer Research Laboratory |
| CI | cast iron |
| | |
| DI | ductile iron |
| DMA | District Metering Area |
| DoD | Department of Defense |
| DOE | Department of Energy |
| DPW | Department of Public Works |
| | |
| EO | Executive Order |
| EPA | U.S. Environmental Protection Agency |
| ERDC | U.S. Army Engineer Research and Development Center |
| ESTCP | Environmental Security Technology Certification Program |
| EXWC | Engineering and Expeditionary Warfare Center |
| | |
| FEMP | Federal Energy Management Program |
| FY | fiscal year |
| | |
| gpm | gallon per minute |
| GWI | global water intelligence |
| | |
| HVAC | heating, ventilation, and air condition |
| | |
| ILA | industrial, landscaping, and agricultural |
| IT | information technology |
| | |
| JBPHH | Joint Base Pearl Harbor Hickam |
| | |
| NAVFAC EXWC | Naval Facilities Engineering and Expeditionary Warfare Center |
| NIST | National Institute of Standards and Technology |
| | |
| O&M | operations and maintenance |
| | |
| PDA | personal data assistant |
| PNNL | Pacific Northwest National Laboratory |
| POI | point of interest |
| psi | pounds per square inch |
| PVC | polyvinyl chloride |

| | |
|---|---|
| rf | radio frequency |
| SIR | savings-to-investment ratio |
| TB | Test Bed |
| UEM | Utility and Energy Management |

# ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Defense Environmental Security Technology Certification Program (ESTCP) under Project Number 201339. The Naval Facilities, Engineering and Expeditionary Warfare Center (EXWC) in collaboration with the U.S. Army Engineer Research and Development Center (ERDC) and Battelle would like to thank Dr. James Galvin for his leadership during the project execution. We are also very thankful for the technical support provided by Mr. Scott Clark and Mr. Glen DeWillie of HydroGeoLogic, Inc., as well as administrative support from Mr. Peter Knowles and Ms. Jane Dudik.

The project team would like to thank the U.S. Army ERDC for hosting both the test bed and field test demonstrations. We also would like to thank Mr. Tony King of the ERDC Public Works for his role in building the test bed and providing operational and testing support throughout the demonstration.

# EXECUTIVE SUMMARY

Reducing water loss at U.S. Department of Defense (DoD) installations is important to preserve potable water needed for essential functions and to limit the drawdown of local water supplies. DoD installations lose significant amounts of water through leaking pipe systems that are near the end of their life cycle. Unfortunately, comprehensive leak detection efforts to identify leaks are not a widespread practice among DoD installations (Pacific Northwest National Laboratory [PNNL], 2013a). However, recent policy from Executive Order (EO) 13693 released in 2015 titled *Planning for Federal Sustainability in the Next Decade* requires installations to take more proactive measures to reduce water loss. Implementation of improved leak detection technologies and the timely repair of water mains supports these Federal and DoD sustainability goals. The DoD Environmental Security Technology Certification Program (ESTCP) supported this project to assess three innovative acoustic leak detection technologies with enhanced cross-correlation features to detect and pinpoint leaks in challenging pipe types, as well as metallic pipes found at DoD installations.

This study was conducted by the Naval Facilities Engineering Command (NAVFAC), Engineering and Expeditionary Warfare Center (EXWC) in collaboration with the U.S. Army Engineer Research and Development Center (ERDC) and Battelle. Test bed and operating distribution system evaluations were conducted at the ERDC facility in Vicksburg, Mississippi. The project objective was to demonstrate and validate the performance of three innovative technologies for leak detection by assessing their ability to detect and accurately locate leaks in challenging pipe types such as polyvinyl chloride (PVC), asbestos cement (AC), and mixtures of pipe types typically found on DoD Installations. The fundamental questions addressed by this study include: Is implementation of these technologies technically feasible for use by DoD installations to reduce water loss and to help meet water and energy conservation goals of the EO? Are these technologies cost effective?

The demonstration evaluated two types of cross-correlating leak detection technologies: 1) a continuous monitoring network approach, and 2) an inspection approach that used sensors temporarily deployed to test segments of pipe within a water distribution system. Three different product lines were tested: one for continuous monitoring and two for periodic inspection of pipe segments. Each technology was demonstrated for detecting and pinpointing leaks in metallic and challenging non-metallic pipe types. For each of the technologies, accelerometers and/or hydrophones were used to detect acoustic signatures of leaks, and time offsets between sensor locations were used to derive leak locations. Performance criteria were established prior to the demonstration, including ability to detect leaks greater than 1 gallon per minute (gpm), pinpoint location within ± 4 feet, achieve less than 5% false positive, and attain a savings-to-investment ratio (SIR) greater than 1. These criteria were established based on querying personnel in DoD Public Works to ascertain their professional judgment and experience regarding effective performance requirements for leak detection.

Evaluations were conducted under controlled conditions at an underground pipeline test bed that was configured with simulated leaks followed by testing under operating conditions within ERDC's water distribution system. The test bed included 11 simulated leaks ranging from 1 gpm to 7 gpm that could be controlled from aboveground. Projected benefits from water and energy

savings and estimated costs for leak detection deployment were also estimated. These projections indicate a SIR greater than 1 for installations with average rates of water main breaks within their water distribution systems. Actual cost-benefit performance should be monitored as leak detection systems are deployed on a site-specific basis.

For the test bed evaluation, only the technology that used an inspection approach and accelerometers met all of the performance criteria. The continuous monitoring technology and the survey technology using both hydrophones and accelerometers did not meet several performance criteria in the test bed evaluation. The simulated leak conditions were successfully detected by all of the technologies. However, the location accuracy varied between the technologies. Two of the three technologies passed the performance objective of locating 90% of simulated leaks within + 4 ft. of the known locations in the test bed. The leak location results for PVC pipe ranged from 86% to 100% within $\pm$ 4 ft. of the known leak locations. False positives were an issue for two out of the three technologies. There is a potential to mitigate false positives in field applications through focused acoustic surveys that are typically conducted at the correlated location prior to marking the leak location. All three technologies were able to detect small leaks at approximately 1 gpm. Challenges were encountered with detecting multiple leaks within a bracketed sensor pair (even though the simulated leaks were spaced more than 5 ft. apart) and in spanning mixed pipe materials. Although the capability to detect and locate leaks under these scenarios was claimed, the leak detections were not as accurate compared to the single leak and single pipe material scenarios within the test bed.

For the operational water distribution testing, two leaks were detected within the portion of the ERDC water distribution system selected for inspection. The limited number of leaks detected in the field tests did not provide sufficient information for the evaluation of the performance criteria (even though visual indications of one leak were observed during the test). Water, energy, and SIR estimates were developed based upon an industry average water main break frequency and regional water and energy cost data.

# 1.0 INTRODUCTION

The U.S. Department of Defense (DoD) Environmental Security Technology Certification Program (ESTCP) has supported a project to assess leak detection methodologies for water distribution systems at military installations. This study was conducted by the Naval Facilities Engineering and Expeditionary Warfare Center (NAVFAC EXWC) in collaboration with the U.S. Army Engineer Research and Development Center (ERDC) and Battelle. Test bed and operating distribution system evaluations were conducted to demonstrate advanced acoustic sensor technologies with enhanced cross-correlation features to detect and pinpoint leaks in challenging underground pipe systems. The demonstration was conducted at the ERDC facility in Vicksburg, Mississippi. The demonstration validated two types of cross-correlating leak detection technologies: 1) a continuous monitoring network approach, and 2) an inspection approach that used sensors temporarily deployed to test segments of pipe within a water distribution system (known as "lift and shift"). Three different product lines were tested including one for continuous monitoring and two for periodic inspection of pipe segments. Each methodology was demonstrated for detecting and pinpointing leaks in metallic and challenging non-metallic pipe types. Evaluations were conducted under controlled conditions at an underground pipeline test bed configured with simulated leaks followed by validation under operating conditions within ERDC's existing water distribution system.

In the original plan, the ERDC demonstration was to be followed by a second field demonstration at Joint Base Pearl Harbor Hickam (JBPHH), a significantly larger military installation that had recently begun to implement advanced metering infrastructure (AMI) technology on the installation's potable water distribution system. The goal was to evaluate the compatibility of the continuous monitoring leak detection technology with the DoD's AMI-enabled water metering infrastructure. Unfortunately, software compatibility and cybersecurity issues at JBPHH precluded the follow-up field demonstration. Other installations were contacted, but had similar issues. Consequently, all leak detection validation efforts were conducted at the ERDC facility for this demonstration effort. Fortunately, the ERDC location provided a good variety of pipe types and challenges for the leak detection equipment. In future efforts, any automated data collection system that relies on installation data systems and infrastructure controls should be evaluated for security concerns prior to initiation of the project. Standards for compatibility with these systems should be developed and provided to parties involved in technology development.

The project contributes to the DoD's water conservation and energy saving initiatives by validating approaches for leak detection in its aging potable water infrastructure. Leaks are commonplace at military bases where pipe distributions systems vary in age, construction, and local site factors (such as stress loading and soil conditions). Some leaks reach the ground surface and can be quickly detected and repaired, while leaks without surface expression may continue undetected for long periods of time, resulting in significant water loss. Advanced leak detection technologies capable of detecting leaks in plastic and metallic pipes can be used to find and repair leaks in a timely manner, potentially saving millions of gallons of water per year.

## 1.1 Background

Water distribution systems at DoD installations were typically installed during initial base construction. Many of these systems are at or near the end of their design life (typically 50 to 75 years). Similar to municipal water distribution systems, these systems are mostly underground, are laid out along streets, roads or in parallel with other utility alignments, and have been expanded over the years. A wide variety of pipe sizes and materials such as ductile iron (DI), cast iron (CI), asbestos cement (AC), and polyvinyl chloride (PVC) have been widely used. Although each installation has a site-specific layout of water meters, pipelines and distribution grids, all share common layout elements. A typical layout is provided in Figure 1-1 showing pipelines leading to administrative buildings, landscaping, and industrial and residential areas. Public Works offices usually have as-built drawings or other historical water utility records that show the relative location of underground pipelines. However, it is important to note that there can be inaccuracies that make it challenging to locate underground water mains, valves, and actual leaks in the field.

The frequency of leaks generally increases with the age of the distribution system, heavy vehicle traffic, and soil settlement. The rate of water main breaks is between 0.21 to 0.27 breaks per mile of pipeline per year according to a recent survey of water utilities (WaterRF, 2015). Leaks are generally not noticed until water rises to the surface and/or until significant amounts of water have been lost over extended periods of time (Fanner et al., 2007; King, 2014). Small leaks can result in considerable cumulative losses if allowed to persist over time. For example, at a leak rate of 1 gallon per minute (gpm) an unrepaired leak could result in a loss of over 500,000 gallons per year. Studies from the U.S. Environmental Protection Agency (EPA) show that on average 14 percent of water consumption is lost through leaks, with some water utilities losing more than 60 percent of water input into the system (EPA, 2012).

Reducing water loss at DoD installations is important to preserve potable water needed for essential functions and to limit the drawdown of available water supplies. Water supply at installations is provided by two types of sources – either an on-site water treatment plant that has access to a source of raw water (either a surface water body or an aquifer), or through connection(s) to a water purveyor. Water purveyors can be local municipalities, quasi-governmental entities such as regional water supply authorities, or private companies. Water used for consumption at installations provided by on-site facilities or purveyors must meet the water quality standards of the Safe Drinking Water Act. Water supplied by a purveyor is purchased as a commodity, based on the volume consumed, and installations must bear the costs of their own water supply operations. Generally, whether an installation has its own water source and treatment system depends on whether established water suppliers were in existence in the area at the time a base was initially developed. On base or other dedicated sources developed by the Government were generally obtained where suitable water could not be purchased from an existing conveyer at the time of initial base construction.


**Figure 1-1. Typical Water Distribution System Layout for a DoD Installation**

There are potential constraints on the availability of water for an installation. Both on-site sources and purveyors must have access to water supplies through purchase from another supplier or through acquisition of rights to a water source. Even where a legal right to a water source exists at a stated rate of use, the natural conditions may further constrain the supply. External supply constraints on a water source may be temporary or long term. Droughts, seasonal changes in weather conditions, climate change, or limitations caused by extraction by other users with valid claims can all limit or reduce the quantity available from a given water supply. California has experienced drought conditions since 2012, and mandatory water reductions have been placed on water systems on a statewide basis. Because California has an intensive system of water resource development and management, conditions that affect sources of water in the Sierra Nevada Mountains can result in reduced supplies at distant use locations, including Southern California and the Central Valley. Multi-year droughts are also relatively frequent occurrences throughout the western United States. Other conditions may temporarily limit water supplies, such as floods that temporarily halt operations at water treatment plants located along rivers or other waterways.

Accurate metering of a water distribution system is essential for billing, tracking water use, and for assessing water losses for water conservation programs. Within installations, irrigated landscapes such as parade grounds and ball fields are typically metered, but not all buildings are individually metered. However, there is a general trend to begin to meter all buildings so that tenant commands can be invoiced for their share of the water consumption. DoD installations are also beginning to implement AMI systems that allow for the review of real-time water use data. However, the meters installed to date have typically been placed on service lines for residential areas, rather than on mainlines or configured in District Metering Areas (DMAs) that could assist in leak detection efforts through water balance methods. Some AMI systems and associated water billing programs have features that can detect abnormally high flows on service lines, which may be the result of a leaky pipeline. Installations are generally responsible for metering accuracy, as well as detecting and repairing mainlines and service lines inside their fence line. These activities are not the installations' responsibility for privatized communities that may be located on or adjacent to the base, but are managed by outside entities. A sound leak detection program should go hand in hand with a quality metering infrastructure in order to support water audits and water loss control program implementation (American Water Works Association [AWWA], 2009).

Water supply constraints are also important due to the costs of operating on-base pumping and treatment systems. The U.S. Army has recognized the strategic need to use water responsibly and to minimize waste. This is evident by the implementation of a novel program called the Net Zero Challenge (Scholze et al., 2012). This program has recruited installations to voluntarily meet aggressive reductions in energy and water use and in waste generation. Net Zero Water installations have the goal to limit potable water consumption. Improved technologies for leak detection are needed to assist these installations in meeting water and energy conservation goals.

Leak detection is critical for cost containment at installations that have high water treatment costs. These conditions are typically associated with energy intensive water treatment processes. For example, at Fort Irwin, a new water treatment plant treating groundwater has a target water recovery goal of 99%, which is higher than other published systems. To reach this high level, a portion of the water will be treated by mechanical vapor recompression, a distillation process that is relatively expensive (Medina et al., 2012). Detecting and repairing leaks can result in reductions in water use, energy demand, and the consumption of water treatment chemicals.

Leak detection is not currently a widespread practice even among installations featured in the pilot efforts for the Army's Net Zero Water Program. Out of the eight utilities in the pilot demonstration, only Tobyhanna Army Depot was noted as having a comprehensive leak detection program (Pacific Northwest National Laboratory [PNNL], 2013a). Previously, conventional leak detection methodologies were limited primarily to time consuming field surveys using sounders (listening sticks) that relied heavily upon operator skill or noise correlators that were tuned for finding leaks in metallic pipes. The detection of leaks in PVC and AC pipes has been particularly challenging because leak signatures are significantly attenuated in these pipe types compared to metallic pipes (Hunaidi, 2000). Leak signatures can travel up to 10 times farther in metallic pipes compared to PVC and AC pipes depending on the pressure, diameter, and material. In addition, periodic repairs may be made that result in mixed pipe materials such as a short PVC repair interspersed within a metallic pipeline, which can lead to

challenges in leak detection. Recent advances in the performance of sensors and in the sensitivity of cross-correlating algorithms have been reported to improve the ability to detect and pinpoint leaks in non-metallic pipelines. These enhanced cross-correlation methodologies are reported to allow for improved resolution of narrow band leak signals, which is helpful for plastic pipes (low frequency sound emission), small leaks, and situations with high background noise (Liu et al., 2012). Another innovative feature tested was the remote cross-correlation capability of sensors deployed in a permanent monitoring network. This is an advance over previous noise logging sensor networks without leak pinpointing capabilities through cross-correlation and/or with operator drive-by required to retrieve the data (Hughes et al., 2014).

The enhanced cross-correlating technologies addressed in this report were assessed in two configurations: 1) continuous monitoring, and 2) intermittent inspections. Continuous monitoring for leak detection is gaining acceptance among progressive municipal utilities looking to minimize water losses. This approach involves the permanent installation of cross-correlating acoustic sensors in a grid pattern to cover the entire water distribution network (or subsets) and provides for real-time leak detection on a daily basis. The second approach was use of these innovative acoustic sensor technologies for intermittent inspections conducted by a trained service provider. The use of periodic leak detection services is also increasing among progressive water utilities within the military. For example, DoD installations in California (such as the NAVFAC Southwest operated facility at Naval Base Ventura County) are looking to contract leak detection audits on a four-year cycle. In addition, studies for the Army's Net Zero Water Program have recommended that the pilot installations "perform ongoing leak detection monitoring and validate meter accuracy as comprehensive approaches to water management" (PNNL, 2013a). The demonstration of the three innovative leak detection technologies provided by this project increases the opportunities for their implementation to improve leak detection and reduce resource consumption and costs under conditions prevalent at DoD installations.

This project enhances the DoD's knowledge base for the inspection of both metallic and non-metallic pipe types and demonstrates innovative acoustic sensor systems that have the potential to address the majority of DoD water pipe network repair requirements. In addition, the project supports DoD in achieving the water and energy conservation goals outlined in Executive Order (EO) 13693, along with sustainability initiatives such as the Army's Net Zero Water and Energy Installation Programs. The timely detection and repair of failing pipe sections are essential steps for preserving the nation's water resources, while limiting damages caused from leaks and breaks, particularly underneath roadways where leaks can undermine surface structures and create hazardous conditions. Through this demonstration, technology performance was quantified related to potential water savings and energy conservation and a return-on-investment was calculated for implementing the leak detection approaches installation wide.

## 1.2 Objective of the Demonstration

The primary project objective was to:

- Demonstrate and validate the performance of three advanced innovative acoustic sensor technologies for leak detection by assessing their ability to detect and accurately locate leaks in PVC, AC, and mixed pipe distribution systems that have been proven challenging for conventional technologies.

Technology benefits were quantified by projecting potential water savings and energy conservation as part of the demonstration project and a return-on-investment was calculated for further consideration of DoD-wide implementation of these leak detection approaches.

A secondary project objective was to:

- Integrate acoustic sensors with AMI networks.

This objective was eventually eliminated from the study due to software compatibility and cybersecurity approval issues.

## 1.3 Regulatory Drivers

The primary regulatory requirement addressed by this research is EO 13693 *Planning for Federal Sustainability in the Next Decade,* which recognizes and supports the need for water conservation efforts by Federal agencies. Improved leak detection technologies also support other sustainability initiatives such as the Army's Net Zero Water and Energy Installation Programs. In addition, states experiencing issues with severe droughts or water supply limitations are increasingly enacting water conservation, water loss control, and water auditing requirements. DoD installations located in these states need to adapt to water supply constraints and/or choose to implement industry best practices to achieve sustainability with respect to water resources, as required by the water conservation goals of the EO.

### 1.3.1 Executive Order 13693

EO 13693, *Planning for Federal Sustainability in the Next Decade*, was issued on March 25, 2015. It supersedes the sustainability goals of previous EOs 13514 and 13423. EO 13693 serves as the current federal regulatory driver for this demonstration project and requires agencies to improve water use efficiency and management as follows:

- Reducing agency potable water consumption intensity, measured in gallons per gross square foot, by 36% by fiscal year (FY) 2025 through reductions of 2% annually relative to a baseline of the agency's water consumption in FY 2007.
- Installing water meters and collecting and utilizing building and facility water balance data to improve water conservation and management.
- Reducing agency industrial, landscaping, and agricultural (ILA) water consumption by 2% annually through FY 2025 relative to a baseline of the agency's ILA water consumption in FY 2010.
- Installing appropriate green infrastructure features on federally-owned property to improve stormwater and wastewater management.

The Federal Energy Management Program (FEMP) of the U.S. Department of Energy (DOE) estimates that the Federal Government used approximately 164 billion gallons of potable water in FY 2007 (FEMP, 2010). The DoD consumed 117 billion gallons of water, representing 71.1 percent of the Federal Government water consumption at an annual cost of $359M. Minimizing

leakage within the water distribution systems at Federal facilities could contribute substantially to meeting the EO 13693 goal of reduced potable water usage. In addition, the installation of water meters required by the EO provides an opportunity to install real-time pressure and leak detection monitoring equipment compatible with a DoD-approved AMI network. This could result in real-time detection of leaks, along with improved data upon which to base a water balance and support management decisions about prioritizing maintenance, repair and replacement of distribution system components.

### 1.3.2 State Regulations and Voluntary Water Industry Standards

Many DoD installations are located in states affected by drought over the past decade. Consequently, there is an increased focus on enacting water conservation, water loss control, and water auditing regulations and initiatives. Drought conditions have persisted within the southwestern United States, resulting in mandates for reductions in water usage. In 2015, the state of California issued EO B-29-15 *State of Emergency Due to Severe Drought Conditions*. The state EO imposes water use restrictions to achieve a statewide 25% reduction in potable urban water usage through February 28, 2016, compared to the amount used in 2013. Based on a survey by the Alliance for Water Efficiency (AWE), several states are adopting industry best practices for calculating water loss similar to the AWWA Manual of Water Supply Practices M36: Water Audits and Loss Control Programs (2009). Over time, states are expected to further adopt the AWWA water audit methodology. Figure 1-2 provides a breakdown of key terms used in this methodology and the relationships of “water losses” and “non-revenue water” as it would apply to both municipal and military installations. It is possible that state requirements could be applied to water utilities that serve DoD installations either as a state regulation or as a voluntary best practice to promote water conservation. Texas, Tennessee, and Georgia have developed water loss reporting methodologies through the state agencies’ requirements to employ water audit methods. The Pennsylvania Public Utility Commission has enacted rules for mandatory water audits starting in 2012. New Hampshire, New Jersey, and Washington require water utilities to implement leak detection if their water losses exceed certain threshold values (AWE, 2012).

<table>
<tr><td rowspan="8">Water Supplied from Own Source</td><td rowspan="11">Total Water Input Volume</td><td rowspan="3">Billed Authorized Consumption</td><td>Billed Water Exported</td><td rowspan="3">Revenue Water</td></tr>
<tr><td>Billed Metered Consumption</td></tr>
<tr><td>Billed Unmetered Consumption</td></tr>
<tr><td rowspan="2">Unbilled Authorized Consumption</td><td>Unbilled Metered Consumption</td><td rowspan="8">Non-Revenue Water (NRW)</td></tr>
<tr><td>Unbilled Unmetered Consumption</td></tr>
<tr><td rowspan="3">Apparent Losses</td><td>Unauthorized Consumption</td></tr>
<tr><td>Customer Metering Inaccuracies</td></tr>
<tr><td>Data Handling Errors</td></tr>
<tr><td rowspan="3">Water Imported</td><td rowspan="3">Real Losses</td><td>Leakage on Transmission and Distribution Mains</td></tr>
<tr><td>Leakage and Overflows at Utility Storage Tanks</td></tr>
<tr><td>Leakage on Service Connections</td></tr>
</table>

**Figure 1-2. Water Audit Method Being Adopted by States (Adapted from AWWA, 2009)**

## 2.0 TECHNOLOGY DESCRIPTION

### 2.1 Technology Overview

All three of the leak detection systems tested in this study are based on acoustic sensor technologies. These systems use one of two types of sensors. The most commonly used sensor is the accelerometer, which measures vibrations in the pipe walls. These vibrations are created by a rapid decrease in water pressure as it passes through the leak opening. These sensors are attached externally to the water line or a fixture such as a valve or hydrant in contact with the water line. The second type of sensor used is a hydrophone, which measures small rapid changes, or pulses, of pressure in the water column passing through the water line. As with the vibrations in the pipe walls, these pulses of water pressure are caused by the water pressure rapidly decreasing as it passes through the leak opening. Hydrophones must be attached to a spigot or hydrant that allows the sensor to be in direct contact with the water in the transmission system.

Determining the location of a leak requires two sensors, one on each side of the leak that can detect the acoustic signature produced by the leak (see Figure 2-1). Each leak produces a relatively constant sound spectrum, characterized by the amplitude of the signal at different frequencies. Both sensors will pick up the same leak signature, but this sound will arrive at each sensor at a slightly different time, due to the varying distances between each sensor and the leak. The difference in time is determined by matching the recorded sound spectrum over time at each sensor. This is accomplished by shifting the spectrum along the time axis until a match is achieved (also referred to as coherence). The time shift and the estimated speed of sound propagation along the pipe wall are used to estimate the difference in distances between the each sensor and the leak. This information, along with the total pipe length between the sensors, allows the software to estimate the position of the leak through cross-correlation.

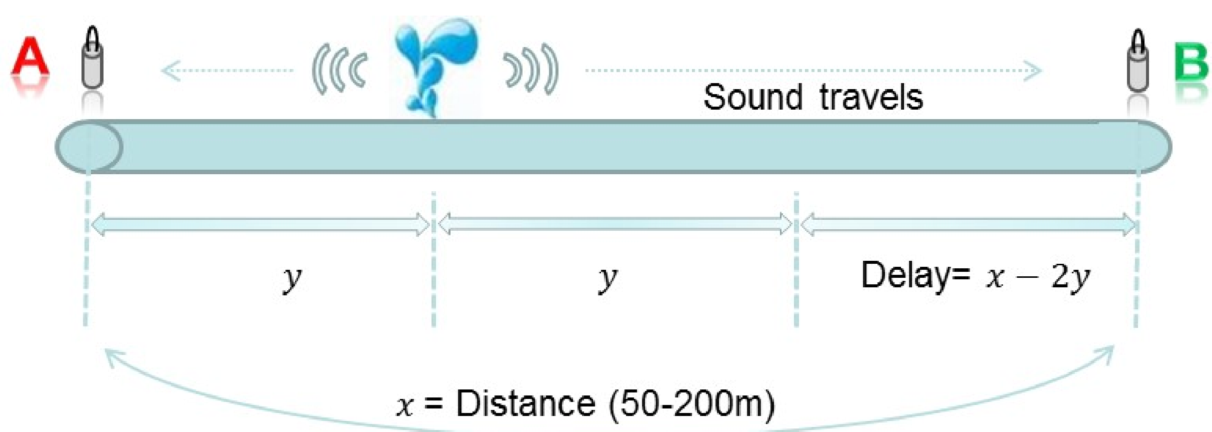



**Figure 2-1. Cross-Correlation Methodology**

The speed at which acoustic signals travel in a pipe are dependent on both the pipe material and diameter. The effective detection range of a sensor will vary based on acoustic velocity, which is correlated with the pipe material and diameter. In general, hydrophones are reported to have a

greater detection range. The accuracy of these systems is dependent on the knowledge of the pipe system to which they are attached, the accuracy of the acoustic velocity in the system, the sensitivity of the sensors, and the capabilities of the analytical software. The representativeness of the acoustic velocity in the system can be improved by direct measurement of the speed of a sound that is artificially induced into the pipe network, such as someone tapping on the pipe. The ability of the software to filter out background noises also increases leak detection and location accuracy.

Table 2-1 provides a comparison of the three innovative leak detection technologies to conventional leak management practices. Each technology was demonstrated to evaluate its ability to accurately detect and locate leaks under controlled conditions in a test bed configuration and under real-world conditions within the ERDC water distribution system.

**Table 2-1. Summary of Innovative Leak Detection Technologies Demonstrated**

| Method of Leak Detection | Technology/ Current Practice | Frequency of Use | Usage/ Ownership | Equipment | Cost Considerations |
|---|---|---|---|---|---|
| **Visual** Visual report of surfacing water or high water usage | Conventional Practice[1] | Ad hoc | NA | NA | • Loss of water prior to detection<br>• Potential damage to nearby infrastructure |
| **Continuous Monitoring** Fixed network monitoring with multiple sensors using acoustic cross-correlation | Gutermann ZoneScan Alpha® | Continuous monitoring for leak signatures | Department of Public Works (DPW) or Utility and Energy Management (UEM) | Sensors, Transmitters, Computer, Personal Data Assistant (PDA) | • Capital equipment<br>• Maintenance<br>• DPW operational labor cost<br>• Contractor installation and setup cost<br>• Annual service fee |
| **Periodic Inspection** Deployed in a "lift and shift" survey using acoustic cross-correlation | Echologics LeakFinderRT™ | Field survey of leak signatures. Recommended every 3-5 years | Contractor | Sensors, Transmitter, Laptop | • Water loss between survey events<br>• Survey costs and contractor expenses |
| | SebaKMT Correlux HL6000X™ | Field survey of leak signatures. Recommended every 3-5 years | Contractor (or purchased by DPW for in-house use) | Sensors, Transmitter, Processor | • Water loss between survey events<br>• Survey costs and contractor expenses |

NA = not applicable

1) Many DPWs do not have in-house staff to conduct routine leak audits and pipeline repairs. Instead, many installations rely on service contracts or in-house contractors to conduct routine repairs and audits.

### 2.1.1 Gutermann ZoneScan Alpha

The ZoneScan Alpha acoustic logger sensor system for continuous monitoring is shown in Figure 2-2. Table 2-2 summarizes the primary components, along with their respective function. System components include: (1) radio repeater modules to send data to a centralized computer processing system; (2) extended antenna (optional to transmit data over longer distances); (3) personal data assistant (PDA) for system setup; (4) communication link for system setup; (5) ZoneScan acoustic sensors; and (6) ZoneScan Alpha Com Link. The system also relies on data management, processing and display capabilities provided by a personal computer system operated by the user and Gutermann's centralized server that provides data processing capability. The sensors are permanently or temporarily installed on valves or fire hydrants at targeted areas of the potable water distribution system. The sensors are easily attached via a magnet on the bottom of each sensor. The sensors can be connected via radio transmission or they can be integrated into an existing AMI network.


**Figure 2-2. ZoneScan Alpha System Components (Courtesy of Gutermann)**
**Note: See Table 2-2 for definition of system elements**

**Table 2-2. Primary Components of the ZoneScan Alpha System**

| Item/No. | Location | Primary Function |
|---|---|---|
| Radio repeater modules (1) | Located near sensor and Alpha Com Link | Relays leak signal data to Alpha unit |
| Extended antenna (2) | Located on the sensor | Supports data transmission |
| PDA for system setup (3) | Operator | Used to set GPS coordinate and synchronize sensors |
| Communication link (4) | Operator | Used to communicate with sensors |
| ZoneScan acoustic noise logger sensors (5) | Water distribution system, valves, hydrants | Acoustic sensors to log leak signal data |
| Alpha Com Link (6) | Nearby building roof or other high location | Collects all data from loggers and sends to server |
| Central Processor (not shown) | Cloud-based server | Data processing and display generation |
| User Computer (not shown) | Users on-station | Provides graphical illustration of piping and displays location of sensors and identified leak locations. |

Table 2-3 summarizes suggested installation parameters and typical acoustic sensor performance. According to the manufacturer, sensor spacing is not impacted by minor bends, valves, or grid layout as long as sensors are properly positioned at nodes (valves or hydrants). Sensors are typically installed as part of a fixed monitoring network within the water distribution system at the spacing intervals identified in Table 2-3. Once installed, they are synchronized, and their physical coordinates captured for graphical display on the ZoneScan.net website. The sensor locations and distribution system layout are displayed on a map overlay, as shown in Figure 2-3.

**Table 2-3. ZoneScan Alpha Sensor Installation and Performance for Leak Detection**

| Pipe Type | Maximum Sensor Spacing on Straight Pipe | Typical Location Accuracy |
|---|---|---|
| PVC | 200 to 250 ft | 1 in. per 250 ft |
| AC | 450 to 500 ft | 1 in. per 750 ft |
| Ferrous | 500 to 750 ft | 1 in. per 1000 ft |
| Steel | 500 to 750 ft | 1 in. per 1000 ft |

Note: Manufacturer-supplied performance specifications. Gutermann does not specify a minimum detectable leak size.

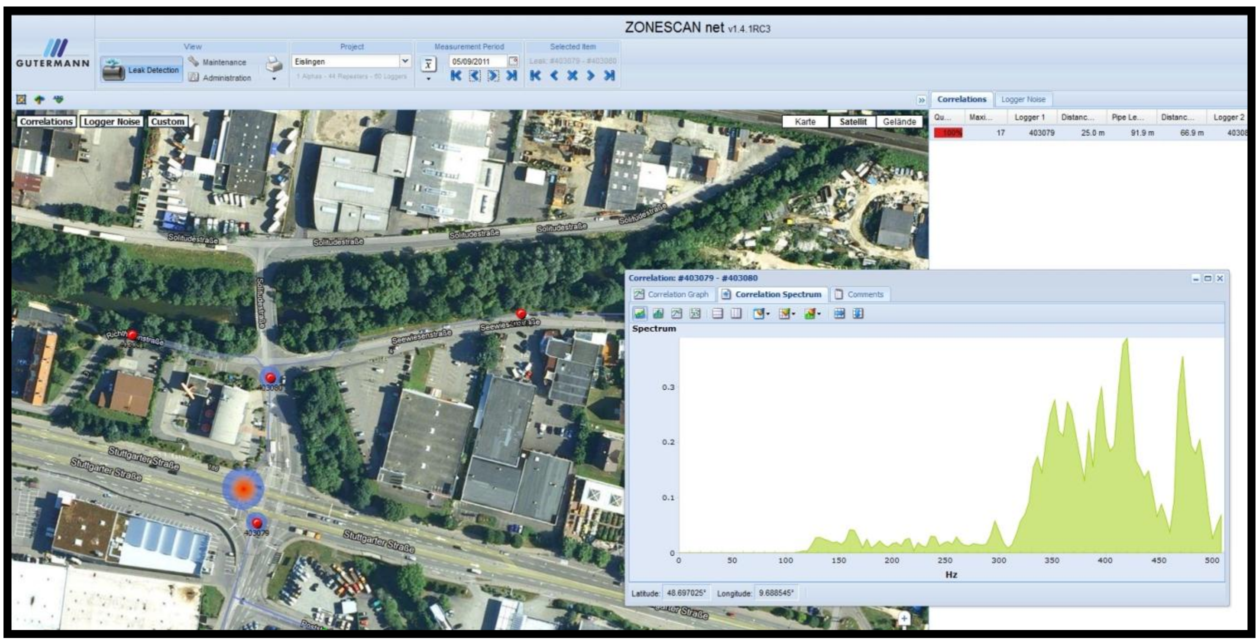



**Figure 2-3. Leak Alert Location and Leak Correlation Spectrum Typical for Large Leak (Courtesy of Gutermann)**

The sensors are programmed to activate at night to monitor for acoustic leak signatures when background noise is at a minimum and pipeline water pressure is highest. For example, the default time period is set for 2:00 to 4:00 am local time with data taken every two seconds over the two-hour interval. After the data collection is complete, the sensors send the data via radio transmission to the data link that connects to the ZoneScan.net server. The sensors are then deactivated to conserve battery life. The server software performs the cross-correlation analysis and generates a display of results when prompted by the end-user. The end-user can graphically display results using the ZoneScan Alpha online software daily and/or be alerted by e-mail when leak-like conditions are detected. If a leak is not identified, the sensor locations will appear on the display in green to signify normal conditions. When the acoustic signal of a leak is detected, the display will show a red dot over the correlated location of the suspected leak in the pipe network (as shown in Figure 2-3), along with corresponding distances from the adjacent sensors. Processing and filtering capabilities within the software algorithm are designed to reduce false positives caused by background noise such as vehicular traffic or heating, ventilation, and air condition (HVAC) systems.

### 2.1.2 Echologics LeakFinderRT

The LeakFinderRT system is deployed to conduct field surveys by placing and moving sensors along pipe segments in a “lift and shift” deployment. After each section of pipe is assessed for leaks, the sensor(s) would be removed (“lifted”) and relocated (“shifted”) to another section of pipeline in the distribution system. The LeakFinderRT system shown in Figure 2-4 is composed of leak sensors (either hydrophone sensors or accelerometers), two transmitters (white/blue), and a central receiver. Technical specifications for the LeakFinderRT system are included in Table 2-4 and sensor types are selected based upon pipe conditions as listed in Table 2-4. The system also includes a wireless radio frequency (rf) signal transmission system and a portable computer. The sensors are attached to two contact points along the targeted pipe section. The location of the contact point differs for each of the two sensor types. The hydrophone sensors are inserted through fire hydrant outlets or other access points that provide direct contact with the water, while the accelerometers are typically placed in direct contact with external components such as fire hydrants, valves or on the pipe wall (via potholes if required to meet sensor spacing requirements).

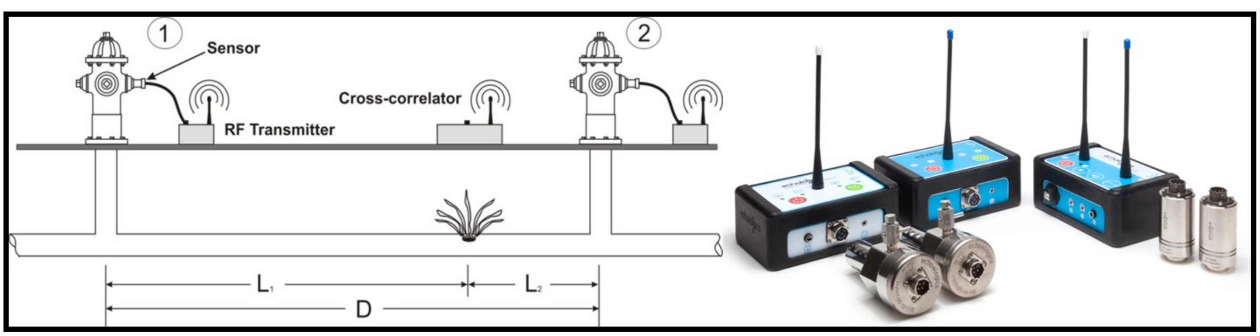



**Figure 2-4. LeakFinderRT System (Courtesy of Echologics [now called LeakFinderST])**

**Table 2-4. Technical Specifications for LeakFinderRT**

| Operational Variable | LeakFinderRT |
|---|---|
| Equipment Logistics | Portable Case |
| Pipe Material | Pit Cast Iron, Spun Cast Iron, Steel, Ductile Iron, Asbestos Cement, Reinforced or Bar-wrapped Concrete, PVC, Polyethylene and other Plastics, as well as lined pipe. |
| Requires Internal Access | Yes for Hydrophones<br>No for Accelerometers |
| Pipe Diameter Range | >12-inch typically use hydrophones;<br><10-inch typically use accelerometers |
| Insertion Requirements | 1.5-inch Tap or Fitting |
| Inspection Distance | 500 to 2,500 feet |

The LeakFinderRT's cross-correlation software runs on a laptop computer. The software was enhanced to provide improved resolution of narrowband leak signals and does not require signal filtering to remove interfering noise. This enhanced cross-correlation method is claimed to provide improved leak detection and location for plastic pipes (low frequency sound emission), small leaks, large diameter pipes (which can attenuate signals), and settings with high background noise (Liu et al., 2012). Table 2-5 summarizes installation parameters and typical acoustic sensor performance specifications for the LeakFinderRT leak detection application.

**Table 2-5. LeakFinderRT Sensor Installation and Performance for Leak Detection**

| Pipe Type | Recommended Sensor Type | Suggested Sensor Spacing | Minimum Detectable Leak Size | Typical Location Accuracy |
|---|---|---|---|---|
| PVC | Hydrophones | Up to 800 ft | 1 to 2 gpm | 3 ft |
| AC | Accelerometers | Over 1,000 ft | 1 gpm | 3 ft |
| Ferrous | Accelerometers | Over 1,500 ft | 1 gpm | 3 ft |
| Steel | Accelerometers | Over 1,500 ft | 1 gpm | 3 ft |

Note: Manufacturer-supplied performance data.

Sensor data are transferred via rf to a portable computer equipped with the LeakFinderRT software. The location of the leak is derived from the equation below:

$$L_1 = \frac{D - c \cdot \tau_{max}}{2} \text{ and } L_2 = D - L_1$$

where:
$L_1$ and $L_2$ are the distances of the leak relative to sensors 1 and 2
c is the propagation velocity of sound in the pipe
D is the distance between the locations of sensors 1 and 2 and
$\tau_{max}$ is the time lag between the two sensors.

Default values can be used for the propagation velocity of sound based on the type and size of pipe or propagation velocity can be determined experimentally in the field to improve the accuracy of the location calculations, as previously described above. During the field survey, the operator reviews the initial analysis on the laptop including displays of coherence and correlation plots to determine if the correlator has identified a leak in between the sensors. When a probable leak is identified, the correlator will provide the distance from the leak to each sensor. The operator will use a manual, hand-held listening probe to confirm the predicted leak location, and will make any needed adjustment to the location and mark the site with biodegradable paint.

### 2.1.3 SebaKMT Correlux

The Correlux HL6000X is a correlator system used for automatically pinpointing leaks in water pipes (see Figure 2-5). It consists of two radio transmitters that connect to piezo-ceramic accelerometers (transmitter A and B), the correlator (the user interface device), correlation software, and headphones. The correlator device can be connected to a personal computer for software updates, downloading data, and to printout results. The correlator device has enough memory to record data for up to 10 segments. It is powered by a battery with an operational life of 12 hours. Each radio transmitter is powered by an internal battery with an operational life of 15 hours. All devices can also be externally powered using a 12-volt direct current car adapter or 110-volt alternating current power supply.

**Figure 2-5. Correlux HL6000X System (Courtsey of Vivax-Metrotech)**

The correlator system works by placing the two accelerometers (sensors) at either end of a pipe section (on valves, exposed pipe sections, or hydrants as the local conditions dictates). Table 2-6 shows the recommended sensor spacing based upon pipe type. The sensor spacing must be accurately measured for input into the correlator if a leak is detected. No information was

available on a minimum detectable leak size or typical location accuracy of the Correlux system. The correlator is activated and the sensor outputs are transmitted to the correlator. Once the correlator unit receives the sensor outputs and inputs data into the correlation software for analysis, the user provides the pipe data including the pipe material, pipe diameter, and pipe length. The device then displays the correlation graph, which compares both signals and provides the distance to the leak. For each correlation, the software automatically sets filters depending on the pipe material, and the filter limits can be adjusted by the user. If a leak is detected, the correlator will provide the leak location in feet away from each of the two sensors. At that point the operator will use a listening probe to validate the leak location at the calculated distance from the sensors. If no leak is detected in the correlator, a zero reading is displayed and one of the sensors can be placed to evaluate the next pipe segment in the field survey.

**Table 2-6. Correlux Sensor Installation Parameters for Leak Detection**

| Pipe Type | Suggested Sensor Spacing |
|---|---|
| PVC | 300 to 500 ft |
| AC | 1,600 ft |
| Ferrous | 2,500 ft |
| Steel | 2,500 ft |

## 2.2 Technology Development

Technology development was conducted by the individual vendors of the leak detection technologies prior to the initiation of the ESTCP project. The overall development of various leak detection and nondestructive evaluation technologies for the inspection of water mains is described in state-of-technology reviews such as Liu et al. (2012) and Hughes et al. (2014). Acoustic leak detection technologies include listening sticks, ground microphones, correlators, noise loggers, and intrusive acoustic sensors (such as tethered hydrophones). As noted previously, recent advances in the performance of sensors and in the resolution of cross-correlating algorithms have been reported to improve the ability to detect and pinpoint leaks in non-metallic pipelines. These enhanced cross-correlation methodologies allow for improved resolution of narrow band leak signals, which is helpful for plastic pipes (low frequency sound emission), small leaks, and situations with high background noise (Liu et al., 2012). Another innovative feature tested was the remote cross-correlation capability of sensors deployed in a permanent monitoring network. This is an advance over previous acoustic logging sensor networks without leak pinpointing capabilities through cross-correlation and/or with operator drive-by required to retrieve the data (Hughes et al., 2014).

## 2.3 Advantages and Limitations of the Technology

This section compares the advantages and limitations of the three leak detection technologies as listed in Table 2-7.

**Table 2-7. Advantages and Limitations of Leak Detection Technologies**

| Leak Detection System | Advantages | Limitations |
|---|---|---|
| ZoneScan Alpha | • Minimally-intrusive system used to locate leaks using correlation methodology<br>• High accuracy in locating PVC leaks for this study<br>• Ability to locate leaks in all types of pipes, including plastic<br>• Ability to detect leaks down to 1 gpm<br>• Remote pinpointing of leaks, reducing man hours needed to search for leaks<br>• Continuous monitoring for leaks and daily updates allows for quick discovery and repair of leaks, reducing water loss<br>• Small size of sensors allows for ease of deployment in existing appurtenances such as manholes, valve boxes or other areas with limited access<br>• Automatically filters out background noise (e.g., pumps and road traffic)<br>• Moderately user-friendly interface | • Overall accuracy of pinpointing leaks did not meet performance objective for this study, although PVC leak location results met the performance objective<br>• Sensor spacing is influenced by both the pipe diameter and material due to the attenuation of the acoustic signal<br>• Access points to install sensors must be available at required sensor spacing, otherwise “potholing” is required to access pipe<br>• Does not provide an indication of leak size<br>• Requires use of proprietary software housed on a non-DoD server<br>• Requires a dedicated frequency for communications within DoD installations |
| LeakFinderRT | • Minimally-intrusive system used to locate leaks using cross-correlation methodology<br>• High accuracy in locating leaks using accelerometer for this study<br>• Ability to locate leaks in all types of pipes including plastic<br>• Ability to detect small leaks down to 1 gpm<br>• Small size of sensors allows for ease of deployment in existing appurtenances such as manholes, valve boxes | • Lower accuracy of pinpointing leaks using hydrophones for this study<br>• Sensor spacing is influenced by both the pipe diameter and pipe material due to the attenuation of the acoustic signal<br>• Access points to install sensors must be available at required sensor spacing, otherwise “potholing” is required to access pipe.<br>• If hydrophones are used, direct access through hydrants |

**Table 2-7. Advantages and Limitations of Leak Detection Technologies (Continued)**

| Leak Detection System | Advantages | Limitations |
|---|---|---|
| | or other areas with limited access<br>• Leak detection can be acquired as a service | or risers is required so direct contact can be achieved between the sensor and water column.<br>• Does not provide indication of leak size<br>• Monitoring duration depends on the quality of the signal, which is influenced by background noise |
| Correlux | • Minimally-intrusive system used to locate leaks using cross-correlation methodology<br>• High accuracy in locating leaks for this study<br>• Leak detection can be acquired as a service<br>• Ability to locate leaks in all types of pipes including plastic<br>• Ability to detect small leaks down to 1 gpm<br>• Small size of sensors allows for ease of deployment in existing appurtenances such as manholes, valve boxes or other areas with limited access<br>• System components are compact, easy to carry in the field, and ruggedized for outdoor use<br>• Headphone connections are available on the unit and on each transmitter to listen to the sensor signal in the field | • Sensor spacing is dependent on the pipe diameter and pipe material due to attenuation of the acoustic signal<br>• Access points to install sensors must be available at required sensor spacing, otherwise “potholing” is required to access pipe<br>• Does not provide indication of leak size |

# 3.0 PERFORMANCE OBJECTIVES

Table 3-1 summarizes the quantitative and qualitative performance objectives for this field demonstration and their corresponding success criteria used to assess progress towards meeting water conservation and energy goals. The key performance consideration is the ability to accurately detect and locate leaks. Once the leaks are pinpointed, repairs can be efficiently made that will reduce overall water loss. Reduction in water loss equates to energy savings both in reduced pumping and water treatment. Leak detection technologies that can accurately detect and pinpoint leaks within $\pm$ 4 feet and produce an acceptable rate of false positives will reduce the overall cost of making repairs. Repair costs are minimized by reducing the area of excavation and surface reconstruction needed to expose the leak and perform the repair. As summarized in Table 3-1, only the performance objectives that were applicable to the test bed leak simulations could be evaluated. The performance objectives associated the operating water distribution system at ERDC could not be validated because an insufficient number of leaks were located during the field tests. The small number of results precluded a meaningful assessment of the field performance measures.

## 3.1 Performance Objectives for Simulated Leak Testing (Test Bed)

This section describes the performance objectives and results as listed in Table 3-1 for the simulated leak testing conducted within the test bed.

### 3.1.1 True Positive Leak Detection Test Bed Conditions

***Purpose*****:** The primary purpose of the test bed with simulated leaks was to validate the reliability of the technologies under a controlled environment. Simulated leaks of several sizes were installed at various locations on an underground pipeline test bed. The exact quantity, location and size of leaks were known by the project team, but not the technology operator so that it could be determined if the detection systems could accurately detect the existence of one or multiple leaks among varying pipe types.

***Metric*****:** Number of correlated leaks displayed on the computer during the operation of the leak detection system. The vendor or team member that operated each respective system, reported and documented the number of correlated leaks displayed on the computer platform. A correlated leak was defined as a detected leak by the vendor's equipment. The results were validated by EXWC technical representatives.

***Data*****:** Number of positive correlated leaks detected and the correlated locations from the sensors (provided in feet).

***Success Criteria*****:** Potential users from DPW at ERDC were queried to determine what would be considered an acceptable accuracy for a leak detection system. Based on their input and the quantity of leaks to be simulated, a 90% accuracy rate in the detection of simulated leaks (less than 10% false negative rate) was selected as the threshold for acceptable performance for detecting leaks under controlled conditions.

## Table 3-1. Performance Objectives for Leak Detection Testing

| Performance Objective | Metric | Data Requirements | Success Criteria | ZoneScan Alpha® | LeakFinderRT (Accelerometer) | LeakFinderRT (Hydrophone) | Correlux HL6000X |
|---|---|---|---|---|---|---|---|
| **Quantitative Performance Objectives (Test Bed Simulated Leak Testing)** | | | | | | | |
| True positive leak detection | Number of Leaks Detected | Acoustic signals | 90% of known leaks detected | Achieved<br>100%<br>(14/14) | Achieved<br>100%<br>(14/14)) | Achieved<br>86%<br>(12/14) | Achieved<br>100%<br>(14/14) |
| False positives | Number of False Positives | Acoustic signals | ≤ 5% of leaks detected were false positives | Not Achieved<br>25%<br>(2/8) | Not Achieved<br>33%<br>(3/9) | Not Achieved<br>22%<br>(2/9) | Achieved<br>0%<br>(0/9) |
| Leak location | Distance (feet) | Distance for leak location | Detected leak locations projected within ± 4 ft of the actual leak location | Not Achieved<br>86%<br>(12/14) | Achieved<br>100%<br>(14/14) | Not Achieved<br>50%<br>(7/14) | Achieved<br>93%<br>(13/14) |
| Minimum detectable leak size | Flow rate (gpm) | Flow rate for known leaks verified in the field with orifice plates | Ability to detect leaks above 1 gpm | Achieved<br>1.0 gpm | Achieved<br>1.0 gpm | Achieved<br>1.0 gpm | Achieved<br>1.1 gpm<br>(exceedance by 0.1 gpm not considered significant) |
| **Quantitative Performance Objectives (Water Distribution System Field Leak Testing)** | | | | | | | |
| True positive leak detection | Number of Leaks Detected | Acoustic signals | 80% accuracy | Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). | | | |
| False positives | Number of False Positives | Acoustic signals | ≤ 20% of leaks detected were false positives | Insufficient field test results located to evaluate performance objectives (see Section 6 for more detailed information). | | | |
| Leak location | Distance (feet) | Distance for leak location | Locate within ± 4 ft | Insufficient field test results located to evaluate performance objectives (see Section 6 for more detailed information). | | | |
| System availability | Amount of time the system is operational (days) | Downtime/uptime | 95% system uptime (after system startup and shakedown) | Achieved<br>96% | Achieved<br>No significant downtime noted | Achieved<br>No significant downtime noted | Achieved<br>No significant downtime noted |
| System reliability | Amount of time system performs as designed (days) | Downtime/uptime | | | Achieved<br>No significant downtime noted | Achieved<br>No significant downtime noted | Achieved<br>No significant downtime noted |
| Estimated water savings in test area | Water loss in gallons per year | Estimated size of remediated leak based on pipe line pressure | Site-specific calculation to achieve SIR > 1.0 | Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). Cost estimates are provided based upon industry-wide information on breakage frequency per mile in Section 7. | | | |

**Table 3-1. Performance Objectives for Leak Detection Testing (Continued)**

| Performance Objective | Metric | Data Requirements | Success Criteria | ZoneScan Alpha® | LeakFinderRT (Accelerometer) | LeakFinderRT (Hydrophone) | Correlux HL6000X |
|---|---|---|---|---|---|---|---|
| Estimated energy savings in test area | Pumping power (kWh) per year | Calculated based on water savings volume and pumping requirements | Site-specific calculation to achieve SIR > 1.0 | Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). Cost estimates are provided based upon industry-wide information on breakage frequency per mile in Section 7. | | | |
| Savings-to-Investment Ratio (SIR) | Ratio of water loss cost savings to leak detection and repair costs. | Cost savings based on the value of water pumped, treated, pressurized, and transported) compared to leak detection costs and leak repair costs | SIR > 1.0 | Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). Cost estimates are provided based upon industry-wide information on breakage frequency per mile in Section 7. | | | |
| **Qualitative Performance Objectives (Test Bed Simulated Leak Testing)** | | | | | | | |
| Ease of use | Ability of installation personnel to use/maintain the technology. | Feedback on ease of use from base personnel compared to current leak detection method; time required for training to use equipment; time required for troubleshooting. | Equal or reduced workload compared to conventional leak detection methodologies (if employed) | Skill Level: Intermediate<br>Sensors: Moderately User-Friendly<br>Desktop Software: Moderately User-Friendly<br>PDA Software: Slightly User-Friendly | Not Applicable (contractor provided service only) | Not Applicable (contractor provided service only) | Skill Level: Advanced<br>Sensors: Very User-Friendly<br>Device: Moderately User-Friendly |
| Operational efficiency gains | Documentation of any operational changes possible as a result of technology. | Feedback from base personnel on changes to O&M process for target area. | Ability of equipment to provide actionable alerts for earlier detection of leaks and/or to focus and prioritize repairs | Insufficient field test results to evaluate performance objectives (see Section 6 for more detailed information). | | | |

***Results***: All three accelerometer sensor based technologies achieved 100% accuracy on notifying that the simulated leaks were present. All 14 leaks were identified by the ZoneScan Alpha, LeakFinderRT accelerometer, and the Correlux HL6000X. However, LeakFinderRT hydrophone-based technology only noted 86% of the simulated leaks and did not achieve the performance objective. See Section 6 for more detailed information.

### 3.1.2 False Positives under Test Bed Conditions

***Purpose***: The ability of the leak detection systems to avoid indication of false positives is a key parameter for a quality detection system. Excavating a pit to find a leak that turns out to be non-existent can exceed several thousand dollars in expenditures, so it is critical that a leak detection system minimizes the rate of false positives.

***Metric***: The number of correlated leaks identified by each technology was compared to the actual number of leaks in the test bed. Several "no leak" scenarios were run on the test bed. This included the following test bed configurations: 1) there were no simulated leaks open on the test bed or 2) there was a simulated leak that was open, but it was located outside of the bracket of the sensors spanning either the DI or PVC pipe. A false positive was indicated if the technology noted that a leak was present between the sensors bracketing the side of the test bed with no simulated leaks in operation. EXWC evaluated the detection of each potential leak and determined if the leak detection system indicated a leak when no simulated leak was operational.

***Data***: The number of false positives identified for each technology.

***Analytical Methodology***: A simple relative comparison of the false positives to the total number of known leaks (i.e., number of false positives/actual number of leaks installed).

***Success Criteria***: <5% false positives.

***Results***: Correlux was the only technology to achieve this objective with no false positives noted. The false positive rate was 25% (2/8) for ZoneScan Alpha, 33% (3/9) for LeakFinderRT with accelerometers, and 22% (2/9) for the LeakFinderRT with hydrophones. It should be noted that standard operating procedures for field deployment call for a focused follow-up acoustic inspection at the correlated leak location, which could help to mitigate false positives in the field environment.

### 3.1.3 Leak Location Accuracy under Test Bed Conditions

***Purpose***: The ability of the technologies to accurately locate leaks was evaluated. If the system was unable to locate leaks within a ± 4-foot interval, then the technology was considered marginal with a lower confidence for finding leaks in a real world scenario. Typically, excavations are made with trench boxes for pipeline repairs. The standard trench box dimensions are 8 feet, 10 feet or 12 feet lengths. The ± 4 feet performance criterion was selected based on assumed use of an 8 foot trench box size.

***Metric***: The distance measured in feet from a control point. The vendor or team member records whether or not a "leak-like" noise was present and specified the cross-correlated distance from a control point.

***Data***: The distance measurement in feet as correlated by the computer system or inspection device and the actual distance (in feet) of the leak from the control points.

***Analytical Methodology***: The computer platform and/or inspection device was used to analyze the acoustic signals from two sensors and a cross-correlating calculation was performed to determine the distance to the leak. The correlated leak location data were compared to the actual distances to the simulated leaks from the control points. The deltas for all simulated leaks were compared to determine the percentage of leaks that were within $\pm$ 4 feet.

***Success Criteria***: 90% of known leaks detected (see Section 3.1.1) and correlated within $\pm$ 4 feet of simulated leak locations.

***Results***: Two out of the four technology configurations achieved this performance objective. The ZoneScan Alpha detected 86% (12/14) of simulated leaks with $\pm$ 4 ft of the known locations. The LeakFinderRT with the accelerometer detected 100% (14/14) of simulated leaks within $\pm$ 4 ft of the known locations. However, the hydrophone version of that technology had a lower performance at only 50% (7/14) simulated leaks detected within $\pm$ 4 ft of the known location. The Correlux detected 93% (13/14) of simulated leaks within $\pm$ 4 ft of the known location.

### 3.1.4 Minimum Detectable Leak Size under Test Bed Conditions

***Purpose***: The ability of each system to detect small leaks in DI and PVC pipe was validated at the test bed. For purposes of this demonstration a small leak was defined as approximately 1 gpm. Leak detection systems that cannot detect leaks of 1 gpm were considered marginal based on discussions with ERDC DPW as a 1 gpm leak equates to over 500,000 gallons per year of lost water.

***Metric***: The vendor or team member operated the respective systems and reported whether or not a correlated leak was determined at the 1 gpm simulated leak locations.

***Data***: Positive acoustic leak signals from vendor. Flow rate as estimated from the simulated leak.

***Analytical Methodology***: EXWC validated whether or not the technology indicates the presence of a leak at 1 gpm.

***Success Criteria***: Ability to positively detect the "minimum" detectable leak of 1 gpm.

***Results***: The tests demonstrated that a leak signature was indicated for a minimum detectable leak size of 1 gpm. All four leak detection technologies were able to detect leaks at approximately 1 gpm.

### 3.1.5 Ease of Use

***Purpose***: The purpose of the "ease of use" qualitative performance objective was to evaluate the technology with respect to the feasibility of implementing leak detection technologies by the DPW staff.

***Metric***: The performance metric assessed the ability of the DPW or team members to use and/or maintain the leak detection equipment and software.

***Data***: Operations and maintenance (O&M) log sheets recorded the time required for training to use the equipment and software. After system shakedown, there was no significant need for repair, maintenance, and/or troubleshooting by DPW or ERDC personnel, so these data were not pursued.

***Analytical Methodology***: DPW and team members using the device were provided a survey to acquire their feedback on the systems.

***Success Criteria***: The success criterion was equal or reduced workload compared to conventional leak detection methodologies. At ERDC, the conventional leak detection methodology was to wait for visual evidence of a leak.

***Results***: The systems were found to require intermediate to advance skills for use in leak detection efforts. The acoustic sensors were rated as moderately to very user-friendly for use. The correlation software/device were rated as moderately-user friendly with the exception of the PDA version of the ZoneScan Alpha, which was rated as slightly-user friendly. More detailed feedback on the ease of use is provided in Section 6.

## 3.2 Performance Objectives for Field Leak Testing (Water Distribution System)

An insufficient number of leaks were located to fully evaluate the performance objectives for the ERDC water distribution system (see Table 3-1). Therefore, detailed discussion and assessment of these individual performance objectives is not possible. Section 6 provides more information on the three potential leaks of interest identified within the ERDC water distribution system. The DPW only chose to excavate one of the three potential leak locations, which did not permit further verification of the leak sizes and/or locations. For this reason, only estimated water savings, energy savings, and savings-to-investment ratio (SIR) values could be calculated. The following preliminary results are noted for the field leak testing within the water distribution system:

- ***True Positive Leak Detection***: Not able to assess; see Section 6 for potential leak locations. Visual evidence of water was noted in the valve box and excavations for two of the detected leaks.
- ***False positives***: Not able to assess; see Section 6 for potential leak locations
- ***Leak location***: Not able to assess; see Section 6 for potential leak locations.

After an extensive shakedown period, uptime for the ZoneScan Alpha sensors was estimated at 96% over a 2-month period from November to December 2014. See Section 6 for additional details on the extended shakedown process caused primarily by sensor communication issues. The LeakFinderRT and Correlux technologies were provided as services and no significant downtime was observed during the field trials. However, on a few occasions, the trials for the LeakFinderRT and Correlux systems needed to be re-run because the equipment needed to reboot and/or the operator wanted to capture additional acoustic leak signature data. The following results are noted for the field leak testing within the water distribution system:

- ***System availability and reliability***: All technologies met the criteria for 95% uptime.

An insufficient number of leaks were identified and/or excavated during field tests to assess likely rates of water loss within the ERDC water distribution system. Cost data were collected for the technologies in order to develop order-of-magnitude cost estimates. Water, energy, and SIR estimates are provided based upon typical breakage frequency per mile as summarized in Section 7.

- ***Estimated water savings in test area***: Water savings were estimated based upon typical breaks per mile. See Section 7 for more details on the calculation methodology.
- ***Estimated energy savings in test area***: Energy savings were estimated based upon typical breaks per mile. See Section 7 for more details on the calculation methodology.
- ***Savings-to-investment ratio***: SIR was estimated based upon technology costs collected from the field demonstration and typical breaks per mile. See Section 7 for more details on the calculation methodology. The SIR estimates suggest that there can be a positive cost outcome for use of these innovative leak detection technologies depending on the level of water loss within the water distribution system.

Operational efficiency gains are expected to be achievable for the ERDC DPW, but could not be quantified. ERDC's current practice is to wait for leaks to surface. As discussed in Section 6, one of the three leaks detected by the field demonstration was already known to the DPW as water was visible at the surface. This was the only leak excavated by the DPW. However, the excavation confirmed that the leak was under the building and not located on the water main. The effectiveness of the cross-correlation technologies in verifying the leak location could not be assessed due to the leak configuration under the building.

- ***Operational efficiency gains***: Insufficient data for assessment at the ERDC water distribution system operation.

# 4.0 FACILITY/SITE DESCRIPTION

The test bed and field demonstration site were located at ERDC in Vicksburg, Mississippi. It is a 673-acre site located in west-central Mississippi, approximately 2 miles east of the Mississippi River (see Figure 4-1). ERDC's Environmental Laboratory is dedicated to providing solutions to environmental and water resource challenges through environmental science and engineering research and development. Therefore, this project fits with ERDC Environmental Laboratory's mission to demonstrate and export technologies throughout the Army, DoD, and the nation.

The ERDC facility was established in the 1930s. The water distribution system varies in age with development of the installation, and has been constructed of several types of materials. The DPW at ERDC manages more than 65,000 linear feet (12+ miles) of distribution system made up of steel, iron, AC, and PVC pipe. More than 42,000 linear feet of the system is aging steel pipe, with steel and PVC repairs located throughout the water distribution system. Figure 4-2 shows the water distribution system layout for the facility. ERDC was selected as the location for the test bed, as the distribution system layout allowed for pipes with artificial defects to be connected to the distribution system for simulated leak testing. The test bed description, its operation, and site conditions are included in this section.

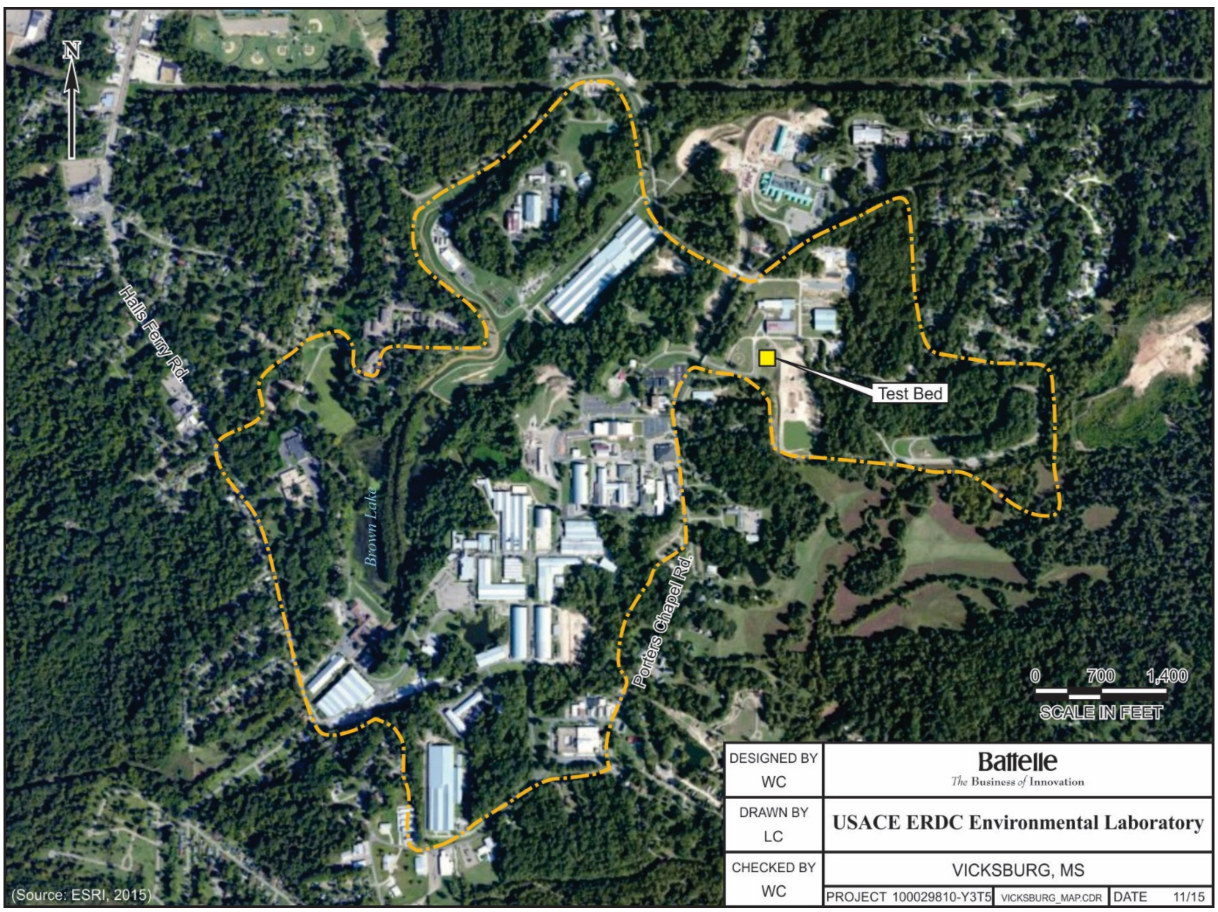



**Figure 4-1. USACE ERDC Environmental Laboratory in Vicksburg, Mississippi (from ESRI ArcGIS, 2015)**

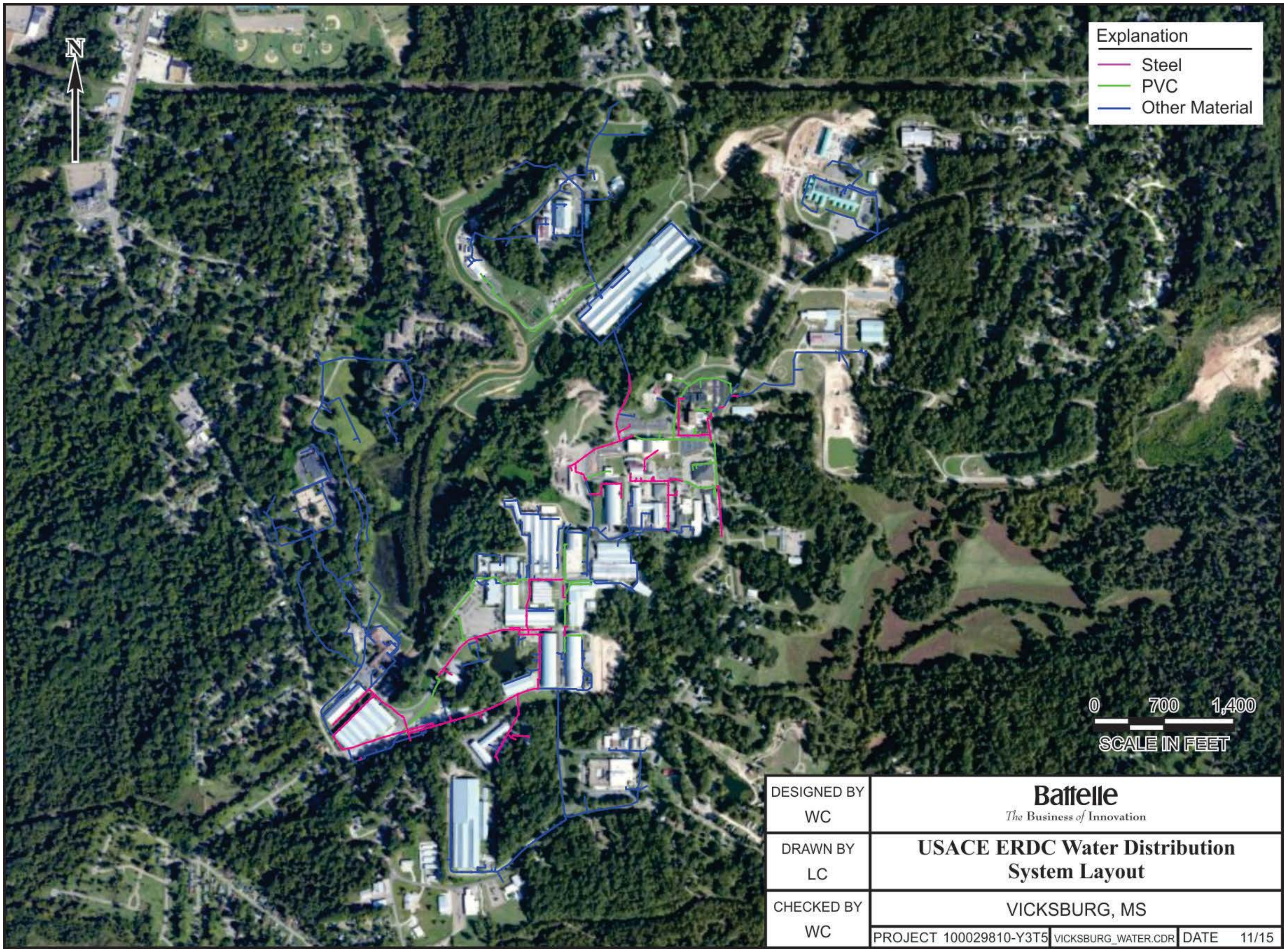



**Figure 4-2. USACE ERDC Water Distribution System Layout (from ERDC and ESRI ArcGIS, 2015)**

## 4.1 Facility/Site Location and Operations

The test bed is located in the northeastern corner of the ERDC campus (see Figure 4-3). It was previously used as part of a hydraulic testing facility with a 6-inch PVC water supply line leading to a large surface impoundment. The site was initially selected for its accessibility, ease of construction and restoration, and available connection to the water distribution system. In addition, the surface impoundment was used to contain water generated from test bed operations. The site was no longer in use for hydraulic testing and there were no activities that could impact the field demonstration.


**Figure 4-3. Test Bed Site Location (from ERDC and ESRI ArcGIS, 2015)**

A 200-foot test bed was constructed for use in the project. The test bed consisted of 90 feet of 6-inch DI pipe and 110 feet of 6-inch PVC pipe. Risers were installed on the test sections to allow for the placement of the acoustic sensors including accelerometers and hydrophones. After test bed construction, 10 simulated leak locations were installed on the main line, along with one simulated leak on a nearby PVC lateral line. The 11 total simulated leaks were established using corporation valves and orifice plates with openings of various diameters (as discussed in Section

5.0). Several views of the test bed site are shown in Figure 4-4 from the installation process through final site restoration.

**Figure 4-4. Test Bed Installation and Configuration**
**(From left: DI pipe, aboveground view, and PVC pipe)**

In addition to the installed test sections, a simulated leak was established on the nearby existing 6-inch PVC supply line that ran 205 feet in length. The purpose of this addition to the test bed configuration was to further evaluate the capabilities of the leak detection technologies on a longer PVC pipe segment. A corporation valve was installed to allow for the use of various sizes of orifice plates to simulate leaks (see Figure 4-5). The pit was subsequently backfilled with gravel and equipped with a sump pump.

**Figure 4-5. Long PVC Run Simulated Leak Pit**

## 4.2 Facility/Site Conditions

The ERDC Environmental Laboratory facility was selected for the demonstration site due to availability of the test location, similarity of infrastructure to existing military installations, and the on-site presence of the project team to facilitate the leak detection studies. The location was an advantage in that the construction of the test bed could occur in any season due to the moderate climate. Also, as a research facility, the team was able to obtain permission from ERDC Security to utilize the necessary bandwidths for sensor communication and data transmission. ERDC is classified as a consecutive water system, which means that it receives potable water from another entity without further on-site treatment. ERDC's potable water supply is from Vicksburg Water and Gas. ERDC does not have its own water tower and/or any additional treatment of the water supplied by the utility. The water system distribution pressure at the test bed area ranges from 90 to 98 pounds per square inch (psi) and averaged 93 psi during the test bed trials. The average cost of potable water is approximately $2.80 per 1,000 gallons, which is the value used in the economic analysis (King, 2015).

# 5.0 TEST DESIGN

This section provides a detailed description of the test bed design and testing procedures used to evaluate the innovative acoustic leak detection sensors.

- **Fundamental Problem**: DoD installations lose millions of gallons of water per year due to undiscovered leaks in aged water distribution systems. An improved approach is needed for reducing water loss by providing DPWs with a cost-effective solution to identify and locate leaks within these aging water distributions systems, especially those constructed of non-ferrous pipes that have proven more difficult for existing leak detection methods. In current practice, DoD installations generally repair distribution systems to address leaks only after surface expression of leaking water is observed.
- **Demonstration Questions**: The key demonstration questions to be answered for each technology are as follows: 1) Does the technology accurately detect and locate leaks in water distribution systems constructed from a variety of materials? and 2) Is it cost-effective?

These questions were assessed under controlled conditions in a test bed configuration. Field testing of an operating distribution system was also conducted, but did not identify a sufficient number of validated leaks to support a quantitative evaluation of the technologies.

## 5.1 Conceptual Test Design

This section provides an overview of key test variables for the controlled test bed and the physical layout of the test facility. Figure 5-1 is a schematic of the test bed, which was 200 ft in overall length and consisted of 6-inch diameter PVC and 6-inch diameter DI pipe.

- **Independent variables**: The independent variables for the controlled test bed included the simulated leak flow rate and the simulated leak location. The simulated leak flow rate was varied through the use of orifice plates of varying sizes installed in the test bed. Several leak locations were installed in the test bed to assess the accuracy of the cross-correlation methods in pinpointing the leak locations.
- **Dependent variables**: The dependent variables included the acoustic signature generated by each leak and the projected leak location as determined by the technologies.
- **Controlled variables**: The controlled variables included the pipeline pressure, the pipe material, the pipe diameter, and the distance between the sensors. The pipeline pressure at ERDC averaged 93 psi as maintained by the water utility. The pipe material was 6-inch diameter PVC and 6-inch diameter DI pipe.
- **Hypothesis**: The hypothesis was that the cross-correlating acoustic sensors could detect and locate leaks within the given performance objectives in a controlled test environment. The controlled test bed provided the setting to determine how accurately each technology could detect and locate leaks.

The test bed provided 11 total simulated leaks installed at known locations. These included five simulated leaks on the 6-inch diameter PVC pipe and five simulated leaks on the 6-inch diameter

DI pipe. In addition, one leak was installed on a lateral "T" off of the test bed. To simulate pipeline leaks, corporation valves were installed with a ¾-inch internal threaded outlet port and a handle affixed to turn the valve on/off from the surface (see Figure 5-2). As shown in Table 5-1, the corporation valves were then fitted with ¾-inch brass orifice plates with drilled holes of various sizes to simulate a range of leak sizes. The flow through an orifice produces a high velocity jet and corresponding negative pressure wave characteristic of a leak signature. The negative pressure wave of a leak is transmitted through the pipe wall and fluid medium. Although not exact, the orifice creates an acoustical signal similar to pressure waves generated from small openings in pipe faults (e.g., pinhole leaks). The estimated flow rate through each orifice was calculated based on the pipeline pressure and Greeley's formula assuming a circular opening (AWWA, 2009). The flow rates ranged from approximately 1 to 8 gpm based on the average 93 psi pipeline pressure at ERDC. Calibration of the leakage rates was conducted in the field as discussed in Sections 5.2 and 5.5. In general, leaks through cracks and joints at the same water line pressure would yield a slightly lower flow rate compared to a circular hole of comparable size based on Greeley's formula (AWWA, 2009). However, varying leak shapes were not studied as part of this demonstration.

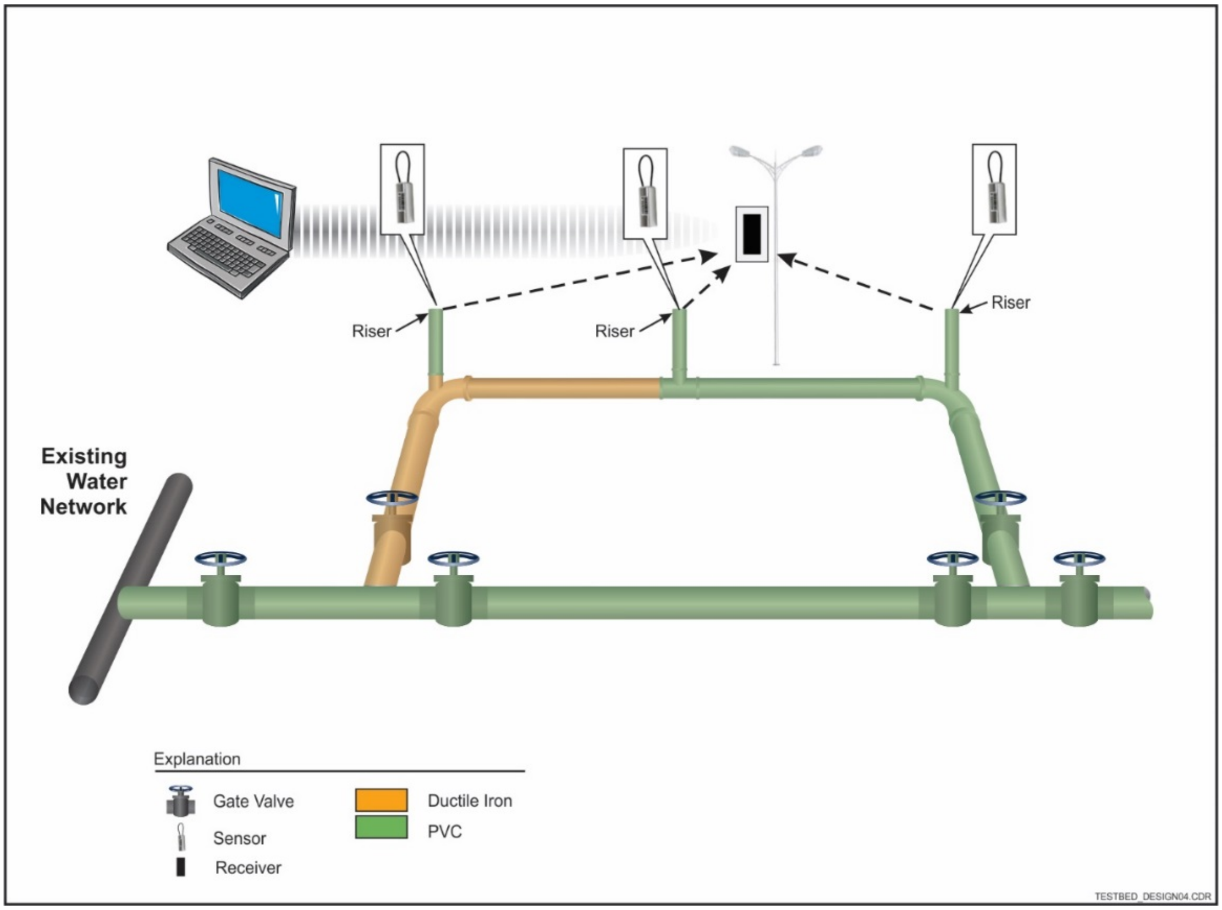



**Figure 5-1. Test Bed Schematic**


**Figure 5-2. Simulated Leak Configuration Using Corporation Valves**

**Table 5-1. Orifice Sizes Used to Simulate Various Leak Sizes during the Demonstration**

| Orifice Size (in.) | Leak Rate (gpm) at 90 psi | Leak Rate (gpm) at 93 psi | Leak Rate (gpm) at 98 psi | Photo |
|---|---|---|---|---|
| 0.187 | 7.9 | 8.0 | 8.3 |  |
| 0.154 | 5.4 | 5.5 | 5.6 |  |
| 0.125 | 3.5 | 3.6 | 3.7 |  |
| 0.0935 | 2.0 | 2.0 | 2.1 |  |

**Table 5-1. Orifice Sizes Used to Simulate Various Leak Sizes during the Demonstartion**

| Orifice Size (in.) | Leak Rate (gpm) at 90 psi | Leak Rate (gpm) at 93 psi | Leak Rate (gpm) at 98 psi | Photo |
|---|---|---|---|---|
| 0.067 | 1.0 | 1.0 | 1.1 |  |

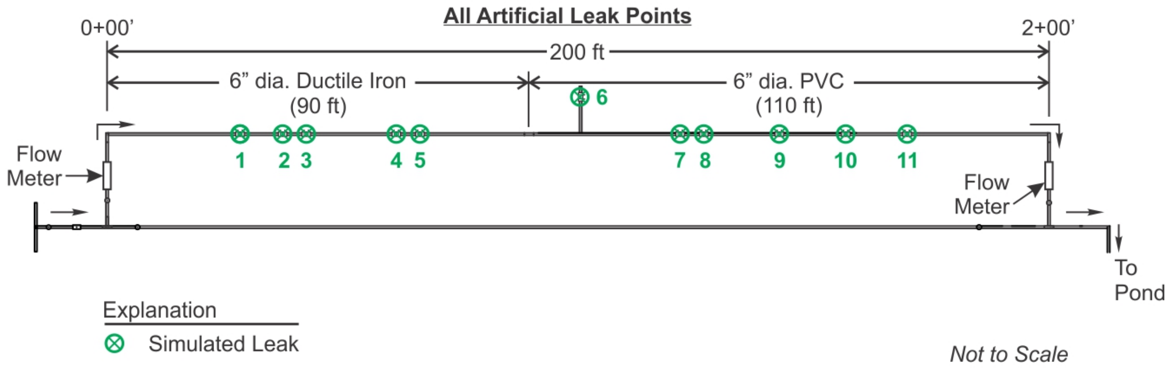
Note: the 0.032 orifice size was installed, but ultimately not included in the demonstration program because the calculated flow rate of 0.23 gpm (at 90 psi) was below the significance threshold for leak size selected for the performance criteria (see Section 3.0).

## 5.2 Baseline Characterization

Baseline characterization included the collection of water distribution system information; the collection of water, energy, and labor costs; and test bed operational parameters. The pipe type and location information was collected from ERDC DPW as shown in Figure 4-2. Discussions were held with ERDC about the optimal location for the test bed and locations to place the acoustic leak sensors out in the water distribution system for field testing, based on considerations such as pipe type, pipe size, and a history of known or suspected water leakage. The following baseline information was collected to support the technology assessment:

- Water Distribution System Parameters (Pipe Type, Sizes): Figure 4-2
- Water Pressure (Minimum, Maximum, and Average): 90 to 98 psi [average 93 psi]
- Unit Water Costs for the ERDC Installation: $2.80 per 1,000 gallons[1]
- Unit Electrical Costs for the ERDC Installation: $0.08 per kW-hr (average commercial rate)[2]
- Personnel labor rates: $20.06/hr Davis Bacon Wage Rate Plus Fringe for Plumber (contractor rate as established for work performed in Warren County in Mississippi. Other regions can exceed $60/hr such as counties in California.)[3]
- As-Built Test Bed Specifications: See Figure 5-3 for leak locations
- As-Built Test Bed Operational Parameters: This section also details baseline data collection related to pressure testing, test bed flow rate measurements, orifice size measurements, orifice flow rate verification (collected aboveground at startup), and temperature. The results of the baseline data collection are presented below.

[1] T. King personal communication, 2015
[2] http://www.electricitylocal.com/states/mississippi/vicksburg/
[3] http://www.wdol.gov and $20.06/hr based on the Davis-Bacon Wage Rate and Fringe for Warren County, Mississippi as of January 2016.




| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

**Figure 5-3. Simulated Leak Locations at ERDC Test Bed**

### 5.2.1 Pressure Testing

To determine the integrity of the pipeline test bed, two pressure tests were conducted from July 16 to 17, 2014 following a standardized procedure adapted from AWWA Standard C605-13. The allowable leakage rate was calculated using the equation shown below:

$$L = (N \times D \times P^{0.5})/7{,}400$$

where
L = leakage rate in gallon per hour (gal/hr)
N = number of joints in the length of pipe tested
D = nominal diameter of the pipe tested in inches (in)
P = average pressure during the leakage test (psi).

As shown in Table 5-2, the results of the two pressure tests for the test bed were significantly below the allowable leakage rate (at 93% to 95% lower). In addition, the 205 ft of PVC pipe adjacent to the test bed that was used for supplemental trials also passed the pressure test with leakage rates at 80% lower than the allowable leakage rate (see Table 5-2).

**Table 5-2. Pressure Test Results**

| Test No. | Test Bed Test 1 | Test Bed Test 2 | PVC Test 1 | PVC Test 2 |
|---|---|---|---|---|
| Date | 07/16/14 | 07/16/14 - 07/17/14 | 1/11/16 | 1/11/16 |
| Start Time | 9:23 | 16:15 | 10:26 | 13:32 |
| End Time | 14:27 | 7:47 | 13:08 | 15:35 |
| Test Duration [hh:mm] | 5:04 | 8:28 | 2:42 | 2:03 |
| No. of Joints (N) | 82 | 82 | 51 | 51 |
| Pipe Diameter (D) [in] | 6 | 6 | 6 | 6 |
| Average Pressure (P) [psi] | 152 | 145.5 | 152.5 | 152.5 |
| Water Added [gal] | 0.22 | 0.50 | 0.28 | 0.22 |
| **Allowable Leakage [gal/hr]** | **0.82** | **0.80** | **0.51** | **0.51** |
| **Actual Leakage [gal/hr]** | **0.04** | **0.06** | **0.10** | **0.09** |

### 5.2.2 Test Bed Flow Rate Measurement

The flow rate of the test bed was measured using two different methods. The first method consisted of recording flow rate measurements at the same time from the two flow meters that were located at each end of the test bed. The results of the three trials conducted on July 31, 2014 are shown in Table 5-3.

Based on the three trials conducted, the overall average flow rate was approximately 24 gpm. The flow velocity was found to be approximately 0.3 ft/sec, which was below the 5 ft/sec upper limit for effective operation of the acoustic leak detection sensors. The vendor indicated that liquid flow velocities above 5 ft/sec cause turbulence that could generate noise and reduce the effective sensitivity of the leak detection system.

**Table 5-3. Test Bed Flow Rates Measured from Flow Meters**

| Trial No. | Flow Rate (gpm) DI Flow Meter[a] | Flow Rate (gpm) PVC Flow Meter[b] | Average Flow Rate (gpm) | Standard Deviation (gpm) |
|---|---|---|---|---|
| 1 | 23.8 | 23.0 | 23.4 | 0.57 |
| 2 | 25.4 | 23.3 | 24.4 | 1.48 |
| 3 | 24.3 | 23.8 | 24.1 | 0.35 |
| | | **Overall Average** | **23.9** | **0.80** |

[a] Located at Station 17 (S17)
[b] Located at Station 18 (S18)

The second method for measuring the test bed flow rate entailed using a 100-gal calibrated tank and recording the time required to fill the tank to the 50-gallon mark. Trial 1 was conducted on July 31, 2014 prior to any simulated leak testing and Trial 2 was conducted on August 1, 2014 following all simulated leak testing. Table 5-4 summarizes the flow rate results for the tank method. The estimated flow rate of 20.8 gpm from the tank test is 13% lower than the average flow meter reading of 23.9 gpm recorded on July 31, 2014.

**Table 5-4. Test Bed Flow Rates Calculated Using Tank Method**

| Trial No. | Date | Mark to Fill (gal) | Time to Fill (min) | Flow Rate (gpm) |
|---|---|---|---|---|
| 1 | 07/31/14 | 50 | 2.4 | 20.8 |
| 2 | 08/01/14 | 50 | 2.5 | 20.0 |
| | | | **Average** | **20.4** |

In addition, a second flow meter was procured in July 2015 to improve the accuracy of flow rate measurements for leak verification studies as described in Section 5.5.

### 5.2.3 Orifice Plate Size and Flow Rate Verification

Prior to start of simulated leak testing, the orifice size and flow rate of each orifice plate were measured and verified. The size of each orifice plate was measured using calipers and compared to the nominal size. The nominal size, measured size, and the relative percent difference are presented in Table 5-5. The measured orifice sizes were all within ± 3% of their corresponding nominal size. Note that the smallest orifice size (i.e., 0.032 inch) was not able to be measured due to the size limitation of the calipers. In addition, this smallest orifice size was not used in the leak demonstration due to the flow rate at 0.23 gpm being below the threshold of interest for the performance criteria (so this data is not included in Table 5-5 or 5-6). Another intermediate size orifice plate (0.0935 inch) was added in later testing for the 205 ft of PVC and lateral leak trials to provide results for additional leak scenarios.

**Table 5-5. Size Verification of Orifice Plates**

| Orifice Diameter | | Relative Percent Difference |
|---|---|---|
| **Nominal (in)** | **Measured* (in)** | |
| 0.067 | 0.065 | 2.99% |
| 0.0935 | 0.0937 | -0.21% |
| 0.125 | 0.127 | -1.60% |
| 0.154 | 0.153 | 0.65% |
| 0.187 | 0.185 | 1.07% |

*Measured using calipers

The flow rates were measured by installing each orifice plate on a riser located at the PVC end of the test bed and recording the time it took to fill a calibrated 5-gallon bucket to a specific depth. The measured flow rate was then compared to theoretical flow rate obtained using Greely's equation. The flow rates were measured on July 11, 2014 and the results of the measurements are summarized in Table 5-6. The relative percent differences between the theoretical and measured flows ranged from 12% to 28% with the measured flow rates tending to be slightly lower than the theoretical calculation would estimate.

**Table 5-6. Summary of Orifice Flow Rates**

| Orifice Size (in) | Area of Orifice ($in^2$) | Pipeline Pressure (psi) | Theoretical Orifice Flow Rate[(a)] (gpm) | Measured Orifice Flow Rate[(b)] (gpm) | Relative Percent Difference (%) |
|---|---|---|---|---|---|
| 0.067 | 0.0035 | 88 | 1.01 | 0.89 | 13% |
| 0.067 | 0.0035 | 88 | 1.01 | 0.90 | 12% |
| 0.067 | 0.0035 | 88 | 1.01 | 0.90 | 12% |
| | | **Average** | **1.01** | **0.90** | **12%** |
| 0.125 | 0.0123 | 90 | 3.54 | 2.85 | 24% |
| 0.125 | 0.0123 | 90 | 3.54 | 2.85 | 24% |
| 0.125 | 0.0123 | 90 | 3.54 | 2.85 | 24% |
| | | **Average** | **3.54** | **2.85** | **24%** |
| 0.154 | 0.0186 | 90 | 5.37 | 4.21 | 28% |
| 0.154 | 0.0186 | 90 | 5.37 | 4.21 | 28% |
| 0.154 | 0.0186 | 90 | 5.37 | 4.21 | 28% |
| | | **Average** | **5.37** | **4.21** | **28%** |
| 0.187 | 0.0275 | 90 | 7.92 | 6.76 | 17% |
| 0.187 | 0.0275 | 90 | 7.92 | 6.78 | 17% |
| 0.187 | 0.0275 | 90 | 7.92 | 6.58 | 20% |
| | | **Average** | **7.92** | **6.71** | **18%** |

(a) Calculated using Greely's equation
(b) Measured using the volume/time method
(c) The 0.032-inch orifice was not used in the demonstration; the 0.0935-in orifice plates size was added later for the long run PVC and lateral trials

### 5.2.4 Temperature Measurements

Water temperature measurements were recorded in the morning and afternoon during each day of the leak detection trials in April and May 2015. The sensor specifications required that the temperature of the water should be between 33°F and 100°F for proper operation. As shown in Table 5-7, all measurements were found to be within the required range.

**Table 5-7. Water Temperature Measurements**

| Date | Temperature (°F) | |
|---|---|---|
| | *Morning* | *Afternoon* |
| 04/29/15 | 74 | 84 |
| 04/30/15 | 62 | 82 |
| 05/04/15 | 84 | 86 |

## 5.3 Design and Layout of Technology Components

This section provides a description of the major technology components for the three innovative leak detection systems. The configurations of the three leak detection systems are similar as they each use similar types of components to detect leaks including: pre-positioned acoustic sensors, transmitters, and software to analyze data and pinpoint leaks using a cross-correlation methodology. However, there are some notable differences in how the technologies are deployed as summarized below.

### 5.3.1 System Design

The primary difference is that the ZoneScan Alpha system is installed as a fixed long-term monitoring network to be operated by local DPW personnel, while the LeakFinderRT and Correlux systems are installed on a temporary "lift-and-shift" basis during a one-time leak detection survey performed as a contracted service. The primary advantage of a fixed monitoring network design would be the continuous monitoring from a central location. This could potentially reduce the required man hours to search for leaks and provide real-time leak notification on a daily basis as leaks emerge. The LeakFinderRT and Correlux technologies are generally deployed via a periodic service contract rather than procured and used by DPW personnel. This approach would be more advantageous for DPWs that do not have local expertise in leak detection and/or prefer to contract out the service. The leak detection survey frequency would need to be determined by the DPW in placing contracts for the service. The ZoneScan Alpha, LeakFinderRT, and Correlux technologies are described in detail in Section 2 with information on their principles of operation and advantages and limitations. This section provides a description of how the technologies were installed and deployed in the field.

**ZoneScan Alpha**: Figure 5-4 shows a schematic and photos of the key components of the ZoneScan Alpha system. The primary components include the ZoneScan acoustic noise logger, radio repeater modules, and Alpha units. The acoustic noise logger was installed on the operating nut of water valves or on fire hydrants via a magnet on the bottom of the sensor. No potholes were made to install the sensors directly on the pipe, although this is a possible configuration. The acoustic sensors analyzed noise on the water lines at scheduled times to pinpoint the location of leaks. The repeaters and Alpha units were then used to transmit the real-time acoustical data to the ZoneScan.net data server. The principles of operation for the ZoneScan Alpha system are described in more detail in Section 2.

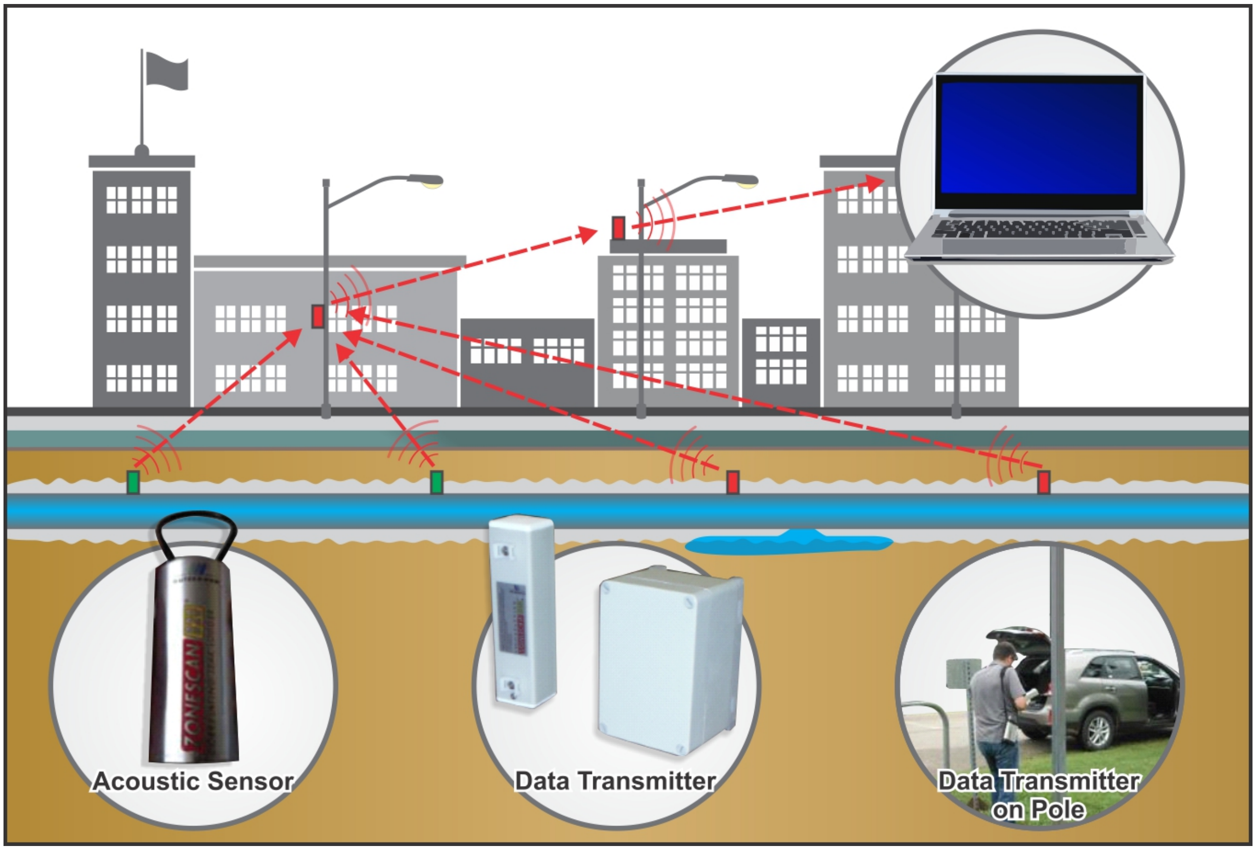



**Figure 5-4. ZoneScan Alpha Installation and Components**

**LeakFinderRT**: As shown in Figure 5-5, the LeakFinderRT system is composed of leak sensors, a wireless signal transmission system, and a personal computer equipped with cross-correlation software. Two acoustic sensors are mounted on water valves, fire hydrants, or exposed pipe in such a way that the pipe interval of interest is located between the sensors. Any active leaks will vibrate the pipe and be detected by the acoustic sensors. The acoustic signals are recorded and a cross-correlation plot generated on a personal computer to pinpoint the location of the leak. The principles of operation for the LeakFinderRT system are described in more detail in Section 2.

**Correlux**: As shown in Figure 5-6, the Correlux system is composed of two leak sensors, a wireless signal transmission system, and a correlating device. Two acoustic sensors are mounted on water valves, fire hydrants, or exposed pipe in such a way that the pipe interval of interest is located between the sensors. Any active leaks will vibrate the pipe and be detected by the acoustic sensors. The acoustic signals are recorded and a cross-correlation plot is generated to pinpoint the location of the leak. The principles of operation for the Correlux system are described in more detail in Section 2.

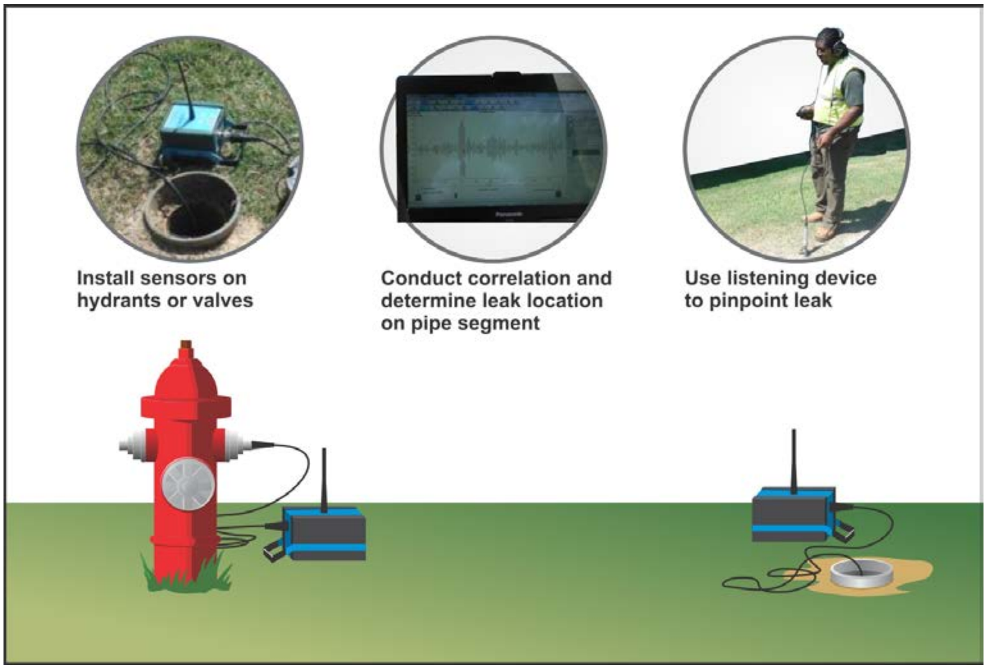



**Figure 5-5. LeakFinderRT Installation and Components**

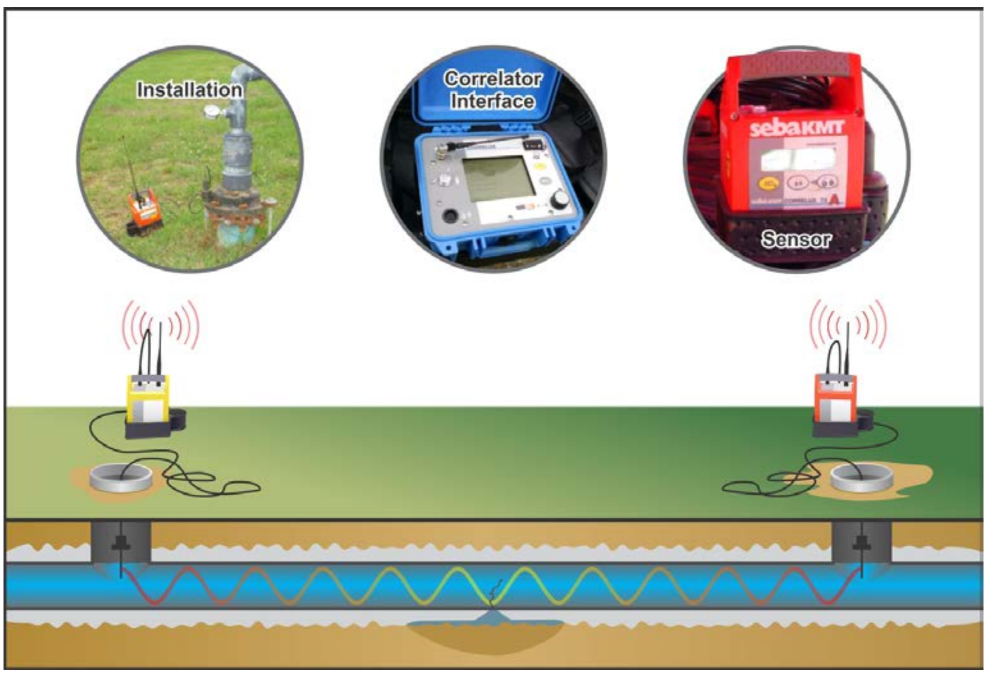



**Figure 5-6. Correlux Installation and Components**

## 5.4 Operational Testing

The operational testing for the test bed was broken down into the following three phases:

- **Phase Test Bed (TB)-1 Collect Reference Data and Site Characterization**: This phase was conducted at project startup in 2013 to collect historic data from the facility in order to review the site-specific characteristics of the ERDC water distribution system. The layout of the water distribution system was reviewed and discussions were held at an on-site meeting in June 2013 to identify areas with a history of suspected leakage and/or water main breaks as discussed with the ERDC DPW. The test bed location was also selected during this meeting. In addition, potable water, energy, and labor costs were collected.
- **Phase TB-2 Installation of the Pipeline Test Bed, Hydraulic Testing, and Setup of Operational Flow Conditions:** Equipment procurement and test bed installation occurred from March through July 2014. ERDC completed installation of the test bed consisting of DI and PVC pipe in July 2014. The original plan was to include concrete pipe as a substitute for asbestos cement pipe (no longer available) for the test bed, but was not available in six inch diameter. Larger concrete pipe is constructed with steel reinforcement and was deemed non-representative of AC, so concrete pipe was not included in the test bed. The simulated leaks of varying sizes were established, along with the installation of a pressure gauge and water meter. The ERDC DPW conducted hydraulic testing to ensure that the pipe held pressure and that there were no unintended leaks within the system (see Section 5.2). The test bed was monitored to ensure that it met the desired operational conditions. Test bed operational conditions were assessed including operational flow, pressure, and temperature measurements as discussed under baseline operating conditions (see Section 5.2).
- **Phase TB-3 Acoustic Sensor Installation, Calibration, and Simulated Leak Testing:** In this phase, the pipeline test bed was used to simulate controlled leak conditions and to validate the performance of the three innovative leak detection technologies. The test bed trials were initially delayed by sensor shakedown issues, which extended from July 22, 2014 through late October 2014. This extended shakedown period was needed to address several issues with the ZoneScan Alpha system primarily involving communications between the sensors, repeaters, and Alpha units. While shakedown was ongoing, preliminary test bed trials were held in July and October 2014 with the ZoneScan Alpha and LeakFinderRT technologies. However, results from these trials were not satisfactory as they primarily involved multiple simulated leak scenarios. See Section 6.5 on the challenges faced by these technologies in detecting multiple simultaneous leaks. After these preliminary trials, a third technology Correlux was included in the demonstration program and the test bed trials were adjusted to focus primarily on single leak scenarios. Testing for the full-scale demonstration with all three technologies proceeded between April and May 2015. During each demonstration run, the leaks were turned on or off using the corporation valves and the leak rates were determined based on the size of the orifice installed at the given location. Each technology was tested under the same leak scenarios. Data collection was conducted for the technology performance assessment. In addition, supplemental trials were conducted in July, September, and December of 2015

to test the technologies on an extended long run of PVC pipe and to repeat the lateral tests with various sizes of simulated leaks.

## 5.5 Sampling Protocol

The sampling protocol resulted in the collection of sufficient data to validate leak detection technology performance under the test bed scenarios. The testing under real-world conditions using the ERDC water distribution system did not result in sufficient positive results that could be excavated for verifications. This portion of the field demonstration was discontinued, although the field test data that were collected are summarized in Section 6. The data collected during the simulated leak testing in the test bed are summarized in Table 5-8. Upon the setup of each test run, the controlled leak information was documented including the selected orifice size(s), the known leak location(s), and the pressure and flowrate through the pipeline. The water temperature was measured twice each day at the start and end of the testing session. After this information was documented for each run of the test bed, the leak detection information was collected from each technology in the form of acoustic leak signals that indicate the positive or negative presence of a leak and the leak location as correlated from both sensors on either side of the test bed.

**Table 5-8. Sample Collection for the Test Bed Leak Detection Trials**

| Data Description | Data Collection Frequency |
|---|---|
| Orifice Size(s) (in) | Once for each test run |
| Simulated Leak Location(s) (ft) | Once for each test run |
| Pipeline Pressure (psi) | Once for each test run |
| Pipeline Flow Rate (ft/s) | Once for each test run |
| Water Temperature ($^oF$) | Start/end of each testing day |
| Detected Leak Signal | Once per test run |
| Detected Leak Correlated Location(s) (ft) | Once per test run from each sensor location |

### 5.5.1 Equipment Calibration and Data Quality

Equipment operation and test bed operational parameters were documented with additional quality checks as described below. This included ensuring proper operation of the flow meters, pressure gauge, and an additional flow verification test performed underground (versus aboveground during system shakedown as described in Section 5.2).

The water meters and pressure gauge were calibrated at the factory points of origin. Additional steps were taken to verify the accuracy of the water meter calibration as described in Section 5.2. In addition, a second flow meter was procured in July 2015 in order to more accurately measure flow rates below 25 gpm. The results of the second flow meter calibration are provided in Appendix A. To determine the accuracy of the flow meter, the flow meter was connected to the cold tap and the other end discharged into a container of known volume. The container was filled to the known volume and the time recorded. The calculated flow rate was then compared to the

instantaneous flow rate indicated on the flow meter. The second flow meter achieved 3.7% accuracy at 1 gpm; 4.3% accuracy at 5 gpm; and 4.8% accuracy at 10 gpm as shown in Appendix A.

After installation of the second flow meter, additional controlled leak flow verification data were collected for the orifice plates while in place underground (see Appendix B). To verify the actual leak size in the test bed locations, a flow meter was attached via a garden hose to a riser and a cold tap (see Figure 5-7). Both the riser and cold tap were connected to the main pipe where the 11 leak orifices were installed. The riser and the cold tap were located on both sides of a valve, so flow through the main pipe could be diverted via the flow meter when the valves were closed. When both valves were closed and a leak was turned "on" with the T-handle, water then flowed up through the cold tap, through the flow meter, and out of each individual leak orifice. The flow meter was then used to indicate the flow rate exiting each leak orifice.

The underground flow verification results are provided in Appendix B. The average of the flow verification results was within 15% of Greeley's formula estimate. Three outliers were identified as follows:

- Leak No. 4 had a low flow of 0.9 gpm versus 3.6 gpm, but was still detected in all trials;
- Leak No. 6 had a low flow of 0.49 gpm versus 1 gpm and a Teflon® tape obstruction was removed before lateral trials were repeated; and
- Leak No. 9 orifice was found to have a large defect and approximately 20 gpm of flow. It was replaced with a new orifice plate (with approximately 3 gpm flow after replacement).

The setup for the underground orifice flow rate testing in shown in Figure 5-7.

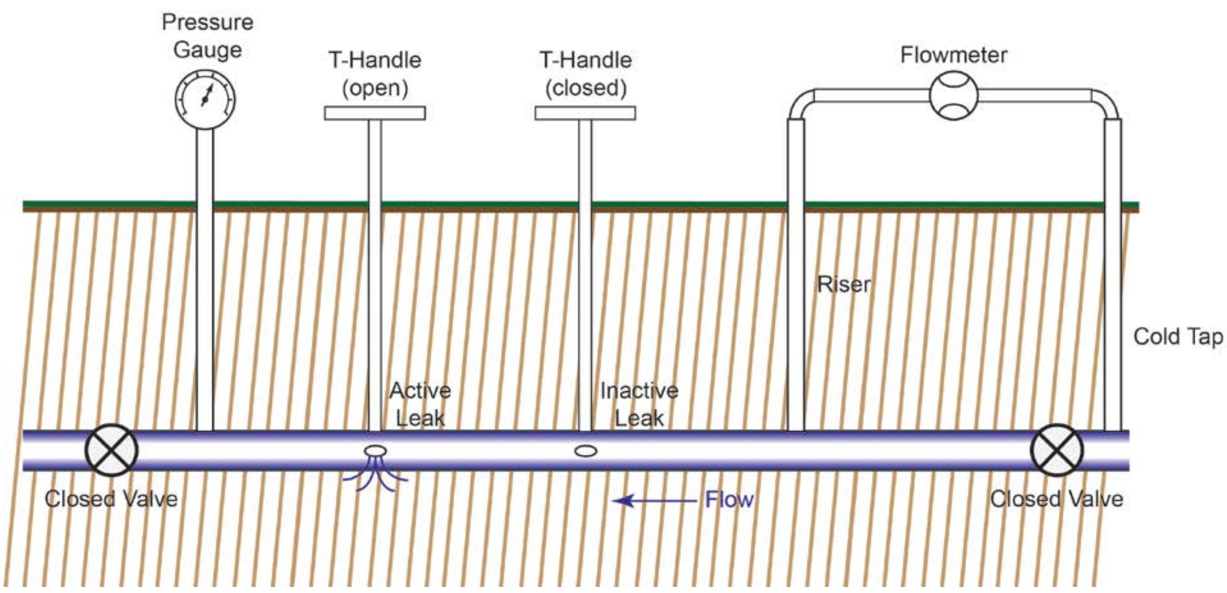



**Figure 5-7. Underground Orifice Verification Setup**

### 5.5.2 Quality Assurance

Quality assurance of the test protocol was accomplished with review of flow meter and pressure gauge readings during each test bed trial run to ensure proper operation and reasonable values.

## 5.6 Sampling Results

The detailed sampling results from the leak detection trials are summarized in Section 6 in order to facilitate evaluation of the technology performance and comparison to performance objectives.

# 6.0 PERFORMANCE ASSESSMENT

## 6.1 Performance Objectives

The performance criteria described in Section 3.0 were used to evaluate the innovative leak detection technologies considered in this study. The performance criteria included both quantitative and qualitative measures and were applied to the test bed results as shown in Table 6-1. Detailed test results for each technology and supplemental testing results are presented in Sections 6.2 through 6.5. Both test bed and field results were collected for the leak detection technologies as presented in these subsections. However, the field test performance criteria could not be assessed due to an insufficient number of leaks identified and/or excavated within the ERDC water distribution system. Therefore, the results are focused on the test bed technology performance evaluation. The performance evaluation of the test bed results provides a basis for selecting leak detection technologies for broader implementation.

**Table 6-1. Technology Performance Results for Test Bed Leak Detection Scenarios**

| Performance Objective[a] | Success Criteria | ZoneScan Alpha | LeakFinderRT (Accelerometer) | LeakFinderRT (Hydrophone) | Correlux |
|---|---|---|---|---|---|
| Detect Known Leaks | 90% of known leaks detected | 100% (14/14) Achieved | 100% (14/14) Achieved | 86% (12/14) Not Achieved | 100% (14/14) Achieved |
| False Positives | < 5% of leaks detected were false positives | 25% (2/8) Not Achieved | 33% (3/9) Not Achieved | 22% (2/9) Not Achieved | 0% (0/9) Achieved |
| Leak Location Overall | Locate 90% of leaks within ± 4 ft | 86% (12/14) Not Achieved | 100% (14/14) Achieved | 50% (7/14) Not Achieved | 93% (13/14) Achieved |
| Leak Location PVC Pipe | Locate 90% of leaks within ± 4 ft | 100% (7/7) Achieved | 100% (7/7) Achieved | 86% (6/7) Not Achieved | 86% (6/7) Not Achieved |
| Leak Location DI Pipe | Locate 90% of leaks within ± 4 ft | 71% (5/7) Not Achieved | 100% (7/7) Achieved | 14% (1/7) Not Achieved | 100% (7/7) Achieved |
| Minimum Detectable Leak Size[b] | Ability to detect leaks above 1 gpm | 1.0 gpm Achieved | 1.0 gpm Achieved | 1.0 gpm Achieved | 1.1 gpm Achieved |
| System Availability/ System Reliability | 95% system uptime | 96% Achieved | 100% Achieved | 100% Achieved | 100% Achieved |
| Ease of use | Ability of installation personnel to use/maintain | Skill Level: Intermediate<br><br>Sensors: Moderately User-Friendly | Not Applicable | Not Applicable | Skill Level: Advanced<br><br>Sensors: Very User-Friendly |

**Table 6-1. Technology Performance Results for Test Bed Leak Detection Scenarios (Continued)**

| Performance Objective[a] | Success Criteria | ZoneScan Alpha | LeakFinderRT (Accelerometer) | LeakFinderRT (Hydrophone) | Correlux |
|---|---|---|---|---|---|
| | | Desktop Software: Moderately User-Friendly<br><br>PDA Software: Slightly User-Friendly | | | Device: Moderately-User Friendly |

a) Insufficient data was were available to assess water savings, energy savings, SIR, and operational efficiency gains.
b) Calculated using the operational pressure and Greely's formula; actual flow rate from the orifice may vary from 0.64 to 0.79 gpm based on flow verification testing.

In addition to the tests summarized above, supplemental leak trials were performed on a longer run of PVC pipe (at 205 feet in total length) and on the lateral located off of the main test bed. These supplemental trials were used to test the limits of leak detection technology performance as summarized in Section 6.5.

### 6.1.1 Detect Known Leaks (True Positive)

The most critical performance measure for a monitoring system is an acceptable rate of true positive results for detecting known leaks in the test bed. Under test bed conditions, the comparison of the result to the monitored condition is straightforward, since the leak being detected is a controlled condition of the test. The calculation for determining the performance criterion is the ratio of detected leaks indicated by the technology to the total leaks present in the pipe interval being evaluated. If less than 100% of the leaks present are detected, the undetected leaks indicate a false negative result. The threshold for the performance criterion acceptability is 90% of known leaks detected for the test bed.

***Results***: All three accelerometer sensor-based technologies achieved 100% accuracy on notifying that the simulated leaks were present. All 14 leaks were identified by the ZoneScan Alpha, LeakFinderRT accelerometer, and the Correlux HL6000X. However, LeakFinderRT hydrophone-based technology only noted 86% of the simulated leaks and did not achieve the performance objective. See Sections 6.2 to 6.4 for more detailed performance information for each technology.

### 6.1.2 False Positive

False positive results for a leak detection technology are also an important consideration for determining acceptable performance. For a leak detection system to be implemented effectively, all indications of leaks must be addressed through field confirmation and repair of any detected leaks. Therefore, a false positive – an indication of a leak provided by the technology that does not reflect actual conditions – would result in evaluation of pipes that are not leaking. The expended effort would directly reduce the cost-effectiveness of the technology.

***Results***: Correlux was the only technology to achieve this objective with no false positives noted. The false positive rate was 25% (2/8) for ZoneScan Alpha, 33% (3/9) for LeakFinderRT with accelerometers, and 22% (2/9) for the LeakFinderRT with hydrophones. See Sections 6.2 to 6.4 for more detailed performance information for each technology. It should be noted that standard operating procedures for field deployment calls for a focused follow-up acoustic inspection at the correlated leak location, which could help to mitigate false positives in the field environment.

### 6.1.3 Location Accuracy

Location accuracy is determined by comparing the actual location of a leak to the predicted location provided by the leak detection technology. The threshold of the performance criterion is a predicted location within ± 4 feet of the actual location. This value was selected based upon the practical consideration that limited accuracy of the location for a leak would require more excavation to expose a leak for repair. Typically, repairs are accomplished with trench boxes to shore up the excavation and 8 feet is a typical size utilized for this purpose. Outside of the ± 4 ft threshold, inaccurate location results would reduce the effectiveness of the leak detection system by requiring more excavation to locate and repair leaks. Because of potential variance of location results with differing pipe materials, this criterion was also reviewed by type of pipe material to determine effectiveness for each material (see Table 6-1).

***Results***: Two out of the four sensor configurations achieved this performance objective. The ZoneScan Alpha detected 86% (12/14) of simulated leaks with ± 4 ft of the known locations. The LeakFinderRT with the accelerometer detected 100% (14/14) of simulated leaks within ± 4 ft of the known locations. However, the hydrophone version of that technology had a lower performance at only 50% (7/14) simulated leaks detected within ± 4 ft of the known location. The Correlux system detected 93% (13/14) of simulated leaks within ± 4 ft of the known location. See Sections 6.2 to 6.4 for more detailed performance information for each technology.

### 6.1.4 Leak Size Threshold

All of the leak detection technologies in this study measure an acoustic signature produced by movement of water through a leak. The signal strength is related in part to the rate of leakage. Considering the signal-to-noise ratio and sensitivity of the sensors, the technologies are expected to have an effective lower limit of leak volume that can be detected under conditions where the systems would be deployed. In order to evaluate this aspect of performance, the controlled conditions of the test bed were varied for each technology to determine whether the technologies could meet an effective leak size sensitivity threshold. Based on economic considerations on the cost of lost water and minimum costs of repair operations, it was determined that an effective leak volume threshold of 1.0 gpm would reflect a suitably reliable condition for detecting leaks that would significantly affect installation costs and resource consumption.

***Results***: The trials in the test bed demonstrated that a leak signature was indicated for a minimum detectable leak size of 1 gpm. All leak detection technologies were able to detect leaks at approximately 1 gpm. See Sections 6.2 to 6.4 for more detailed performance information for each technology.

### 6.1.5 System Operational Availability and Reliability

System availability and reliability are represented by the ratio of the time that a monitoring technology is effectively providing leak detection to the total time of the test period. As a technology's reliability increases and monitoring results are provided over more of the test period, the system availability and reliability approach 100%. The performance of the leak detection systems by these criteria are relevant for field test conditions, as system availability is relevant to a distribution system that is on line the vast majority of the time.

***Results***: All technologies met the criteria for 95% uptime. After an extensive shakedown period, uptime for the ZoneScan Alpha sensors was estimated at 96% over a 2-month period from November to December 2014 as shown in Table 6-2. However, an extended shakedown period was needed from July 22, 2014 to October 2014 to address several issues involving sensor communications. These issues were primarily related to malfunctioning of repeaters and alpha units that required replacement and/or relocation to improve more consistent access to the sensor data. All issues related to the system were fully addressed by October 2014 and satisfactory operations were achieved from that point forward. The LeakFinderRT and Correlux technologies were provided as services and no significant downtime was observed during the field trials. However, on a few occasions, the trials for the LeakFinderRT and Correlux systems needed to be re-run because the equipment needed to reboot and/or the operator wanted to capture additional acoustic leak signature data.

**Table 6-2. Reliability of the Gutermann ZoneScan Sensors during Example Operational Period (After System Shakedown from July to October 2014)**

| Time Period | No. of Days | No. of Sensors | No. of Sensor-Days | Non-Operational Sensor-Days | Operational Sensor-Days | % Time Operational |
|---|---|---|---|---|---|---|
| November 1-30, 2014 | 30 | 19 | 570 | 18 | 552 | 96.8% |
| December 1-31, 2014 | 31 | 19 | 589 | 26 | 563 | 95.6% |
| **Overall Reliability** | | | **1,159** | **44** | **1,115** | **96%** |

### 6.1.6 Water Loss Reduction

An insufficient number of existing leaks were identified and/or excavated during the field test on the operating distribution system to assess likely rates of water loss within the ERDC water distribution system. Water savings were estimated based upon typical breaks per mile. See Section 7 for more details on the calculation methodology.

### 6.1.7 Energy Use Reduction

Due to insufficient data from the field trials as described above, energy savings were estimated based upon typical breaks per mile. See Section 7 for more details on the calculation methodology.

### 6.1.8 Savings-to-Investment Ratio (SIR)

Due to insufficient data from the field trials as described above, SIR values were estimated based upon technology costs collected from the field demonstration and typical breaks per mile. The SIR estimates suggest that there can be a positive cost outcome for use of these innovative leak detection technologies depending on the level of water loss within the water distribution system. See Section 7 for more details on the calculation methodology.

### 6.1.9 Ease of Use and Operational Efficiency Gains

Qualitative performance measures considered for the tests of leak detection technologies include ease of use and operational effectiveness. Both are based on experience of test personnel during field deployment of the techniques on an active distribution system

**Ease of Use**: This qualitative performance measure is based on reported experience by field operators regarding the level of difficulty in operating the systems and gathering results. Ease of use is dependent on complexity of the setup and operation of equipment, quality of documentation on equipment operation, and susceptibility of equipment to outside sources of interference or other effects that complicate field operations. The ease of use was assessed by team members that had utilized the ZoneScan Alpha and Correlux equipment during the field demonstration project. The LeakFinderRT was performed as a service so was not assessed for this performance criterion.

For the ZoneScan Alpha system, it was estimated that one week was required to become familiar with the technology operations and capabilities. It was rated as requiring intermediate skills to operate. The leak detection components (i.e., sensors) and cross-correlation software (on the desktop) were rated as moderately user-friendly for deployment in the field for leak detection efforts. The leak detection software on the PDA was rated as slightly user-friendly because some issues were encountered related to syncing the sensors with the tablet and connection to the ZoneScan Alpha Web site from the PDA. The main advantages of the system were viewed as the continuous monitoring for early detection of leaks, the automated leak alerts, and the ability to easily reposition sensors in a “lift-and-shift” mode. The main limitations cited were that better tutorials or help files would be beneficial to new users, more options should be available to install the software on local servers versus in the cloud, and issues with ease of use of the PDA version of the correlation software. The system was recommended for in-house use by one team member and to be contracted as a service by another team member.

For the Correlux unit, it was estimated that one day was required to become familiar with the technology operations and capabilities. It was rated as requiring advanced skills to operate. The leak detection components (i.e., sensors) were rated as very user-friendly, while the cross-correlation device was rated as moderately user-friendly for deployment in the field for leak detection efforts. The team member agreed that overall it was easy to utilize the correlation software. The main advantages of the system were viewed as its straight forward operation and the short correlation time of about five minutes. The main limitations cited were that a more detailed training program would be needed to properly recognize and evaluate leak signatures and to be able to eliminate false positives. In-house use of the Correlux technology was

recommended if the equipment was to be used periodically to locate or confirm suspected leaks. If a large installation was going to survey a large area, it was recommended to procure this technology as a service due to the time and manpower requirements.

**Operational Effectiveness**: This qualitative measure is based on a comparison of the level of effort to maintain and use the innovative leak detection systems in comparison to the conventional approach. Leak detection by other means could include evaluation of metering data and comparison of reported usage rates within the distribution system and/or field evaluation and observation of surface expression of leaks, such as wet ground in dry weather conditions or unexplained presence of water in utility vaults or other underground structures. Insufficient data were available to evaluate this performance objective as there were no pre-existing water meters at ERDC DPW and leak detection was only on a reactive basis in response to water main breaks (as is common practice for many U.S. water utilities).

## 6.2 ZoneScan Alpha Testing Results

### 6.2.1 Test Bed Results

Testing of the ZoneScan Alpha leak detection system was performed on April 29 and 30, 2015. The system was evaluated for true positive, false positive, location accuracy and leak size threshold performance criteria at the test bed. The test bed layout is described in Section 4 and the basic configuration and execution of the test bed evaluations are provided in Section 5. The test bed results for ZoneScan Alpha are summarized in Table 6-3. Depictions of the projected and known leak locations are presented in Figures 6-1 and 6-2 for PVC and DI pipe materials. False positive data are presented in Table 6-4. These results were compared to the performance criteria as part of the technology performance assessment.

The ZoneScan Alpha system provided 100% reliability in providing leak detection (true positive) results for the controlled conditions of the test bed (see Table 6-3). Location results were moderately accurate. On the PVC section of the test bed, the ZoneScan Alpha system identified seven out of seven leaks within ± 4 ft. On the DI portion of the test bed, the system identified five out of seven leaks within ± 4 ft. Overall, the ZoneScan Alpha detected 86% (12/14) of simulated leaks within ± 4 ft of the known locations. The system was found to have a false positive rate at 25% (2/8) and did not pass this criteria (see Table 6-4). However, the usual protocol would call for the operator to perform a focused acoustic inspection at the correlated location before excavation, so it is possible this helps to minimize false positives in the field environment. The system was found to be sensitive to detect leaks at approximately 1.0 gpm in both PVC and DI pipe. Overall, the ZoneScan Alpha system met the performance objectives for leak detection, small leak detection, and leak location only on the PVC pipe. The remaining performance objectives related to leak location on the DI pipe and false positives were not met.

### 6.2.2 Field Test Results

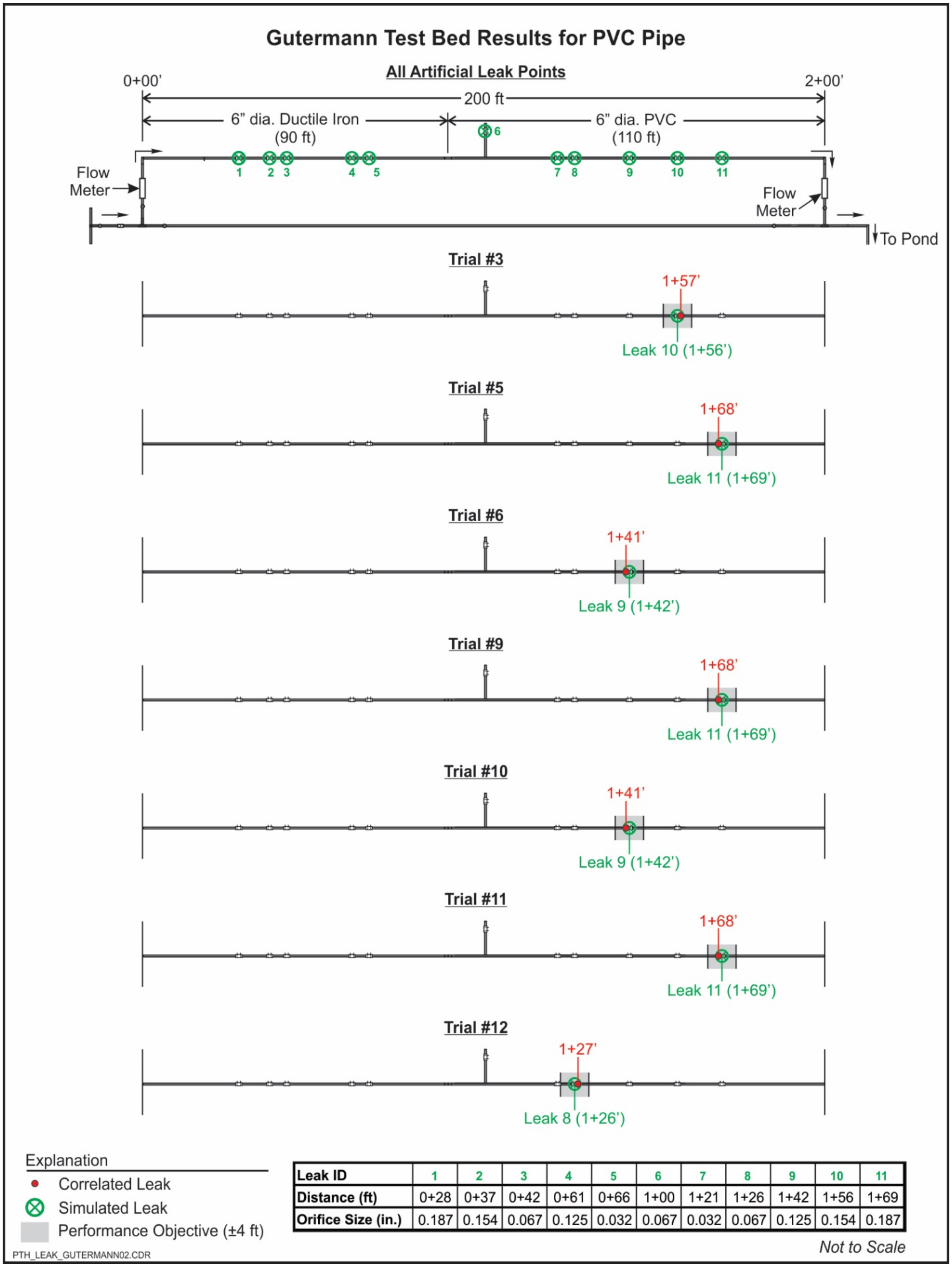
Field testing of the ZoneScan Alpha system was conducted from July 22 to December 31 2014. The sensor spacing is listed in Table 6-5. The total length of pipe surveyed was 4,325 ft of steel, PVC, and DI pipe. The field test detected one potential leak in Area B between Sensors 6 and 7 in the vicinity of Mississippi Road (see Figure 6-3). A manual correlation was performed on the

sensors on August 1, 2014 to determine the location of the leak. The location of the leak was calculated to be 81.5 feet to the west of Sensor 7. Figure 6-4 shows a screenshot of the results of the manual correlation. The location was investigated by Battelle and ERDC staff and a valve was found in the vicinity of the correlated leak location. When the lid of the valve box was removed, the box was full of water despite there being little to no precipitation that week (see Figure 6-5). Based on the distance from Sensor 7 to the correlated leak (i.e., 81.5 feet) and to the valve (i.e., 77.2 feet), the valve was believed to be the source of the leak. However, the suspected leak location was not excavated so the source of the leak could not be fully verified. The correlated leak location was within 4.3 feet of the valve location. The indication of a leak in the vicinity of the valve was reported on the ZoneScan Alpha website for 119 days until November 18, 2014. The DPW is reported to have later adjusted the valve and the leak signature was no longer present after this date. While the field test did indicate that the system successfully detected a probable leak, the indication of only one leak in the field test did not provide sufficient information for evaluation of performance criteria for this portion of the work.

**Table 6-3. Results Summary for the ZoneScan Alpha Test Bed Evaluation**

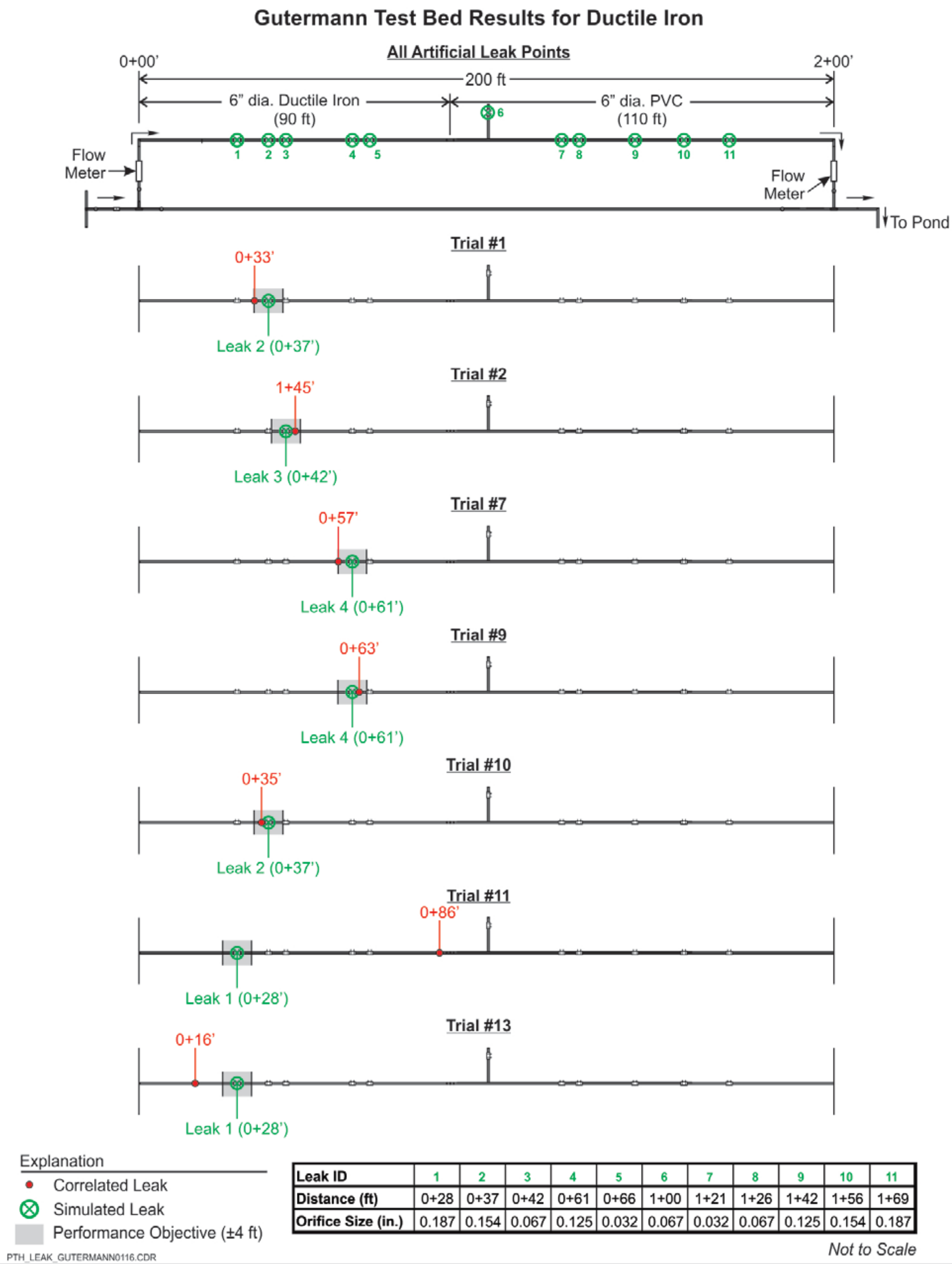
| Trial No. | Pipe Material | Leak No. | Distance to Leak(a) | Pressure | Estimated Leak Flow Rate(b) | Correlated Leak Distance(a) | Accuracy | Within Performance Objective(c) |
|---|---|---|---|---|---|---|---|---|
| # | – | # | (ft) | (psi) | (gpm) | (ft) | (ft) | (Y/N) |
| 3 | PVC | 10 | 156 | 92 | 5.4 | 157 | 1 | Yes |
| 5 | PVC | 11 | 169 | 92 | 8.0 | 168 | 1 | Yes |
| 6 | PVC | 9 | 142 | 92 | 3.6 | 141 | 1 | Yes |
| 9* | PVC | 11 | 169 | 92 | 8.0 | 168 | 1 | Yes |
| 10* | PVC | 9 | 142 | 94 | 3.6 | 141 | 1 | Yes |
| 11* | PVC | 11 | 169 | 94 | 8.1 | 168 | 1 | Yes |
| 12 | PVC | 8 | 126 | 94 | 1.0 | 127 | 1 | Yes |
| 1 | DI | 2 | 37 | 92 | 5.4 | 33 | 4 | Yes |
| 2 | DI | 3 | 42 | 94 | 1.0 | 123 (45)[d] | 81 (3)[d] | Yes |
| 7 | DI | 4 | 61 | 92 | 3.6 | 57 | 4 | Yes |
| 9* | DI | 4 | 61 | 92 | 3.6 | 63 | 2 | Yes |
| 10* | DI | 2 | 37 | 94 | 5.5 | 35 | 2 | Yes |
| 11* | DI | 1 | 28 | 94 | 8.1 | 86[e] | 58[e] | No |
| 13 | DI | 1 | 28 | 92 | 8.0 | 16[e] | 12[e] | No |
| **Number of Leaks Detected** | | | | | | | **14/14** | **100%** |
| **Number of Correlated Distances within ± 4 ft (Overall)** | | | | | | | **12/14** | **86%** |
| **Number of Correlated Distances within ± 4 ft (PVC)** | | | | | | | **7/7** | **100%** |
| **Number of Correlated Distances within ± 4 ft (DI)** | | | | | | | **5/7** | **71%** |

(a) All distances are referenced from 0 ft
(b) Calculated using the pressure and Greely's formula
(c) Performance objective is ± 4ft of actual leak location
(d) With default filter applied (122 to 512 Hz) correlated leak distance is within 3 ft
(e) With default filter applied (122 to 512 Hz) correlated leak distance does not change
* Trial conducted with two leaks turned on; one on each pipe material.




| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

**Figure 6-1. ZoneScan Alpha Test Bed Leak Location Results for PVC Pipe**




| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

**Figure 6-2. ZoneScan Alpha Test Bed Leak Location Results for DI Pipe**

**Table 6-4. Summary of False Positive Results for ZoneScan Alpha System**

| Trial No. | Leak No. | Pipe Material | DI Bracket Correlation Result[(a)] (ft) | PVC Bracket Correlation Result[(a)] (ft) | False Positive (Yes/No) |
|---|---|---|---|---|---|
| 1 | 2 | DI | 33 | OOB | No |
| 2 | 3 | DI | 123 (45) | OOB | No |
| 3 | 10 | PVC | OOB | 157 | No |
| 4 | None | NA | OOB | ND 129[b] | No |
| 5 | 11 | PVC | OOB | 168 | No |
| 6 | 9 | PVC | 84 | 141 | Yes |
| 7 | 4 | DI | 57 | OOB | No |
| 12 | 8 | PVC | Logger Error | 127 | NA |
| 13 | 1 | DI | 16 | 89 | Yes |
| **Number of False Positives** | | | | **2/8** | **25%** |

OOB = out of bracket; NA = not available
(a)All distances are referenced from 0 ft
(b) Low quality signal at 10% so considered non-detect (ND)

**Table 6-5. Spacing of ZoneScan Alpha Sensors**

| Sensor No. | Pipe Material | Pipe Size | Distance | Distance |
|---|---|---|---|---|
| **Area A** | | | | |
| S1 | PVC, Steel | 6" | – | S1 to S2 = 685 ft |
| S2 | Steel | 6" | S1 to S2 = 685 ft | S2 to S3 = 345 ft |
| S3 | Steel | 6" | S2 to S3 = 345 ft | – |
| **Area B** | | | | |
| S4 | Steel, PVC | 6" | – | S4 to S5 = 285 ft |
| S5 | PVC | 6" | S4 to S5 = 285 ft | S5 to S6 = 190 ft |
| S6 | Steel, PVC | 6" | S5 to S6 = 190 ft | S6 to S7 = 264 ft |
| S7 | PVC, Steel | 6" | S6 to S7 = 264 ft | S7 to S8 = 400 ft |
| S8 | Steel | 6" | S7 to S8 = 400 ft | S8 to S9 = 332 ft |
| S9 | Steel | 4" | S8 to S9 = 332 ft | – |
| **Area C** | | | | |
| S10 | PVC | 6" | – | S10 to S11 = 360 ft |
| S11 | PVC | 6" | S10 to S11 = 360 ft | S11 to S12 = 240 ft |
| S12 | PVC | 6" | S11 to S12 = 240 ft | S12 to S13 = 230 ft |
| S13 | PVC | 6" | S12 to S13 = 230 ft | – |
| **Area D** | | | | |
| S14 | PVC | 6" | – | S14 to S15 = 385 ft |
| S15 | PVC | 6" | S14 to S15 = 385 ft | S15 to S16 = 410 ft |
| S16 | PVC | 6" | S15 to S16 = 410 ft | – |
| S17* | Ductile Iron | 6" | – | S17 to S18 = 199 ft |
| S18* | PVC | 6" | S17 to S18 = 199 ft | – |

*Sensor located on test bed


**Figure 6-3. Map of Area B ZoneScan Alpha Sensors (from ESRI ArcGIS, 2015)**


**Figure 6-4. Manual Correlation between Sensors 6 and 7 in Area B on August 1, 2014**

**Figure 6-5. Water-filled Valve Box in Vicinity of Leak Detected by ZoneScan Alpha System**

## 6.3 LeakFinderRT Test Results

### 6.3.1 Test Bed Results

Testing of the LeakFinderRT leak detection system was performed on May 4, 2015 and included trials for each of the two different sensor configurations (e.g., accelerometer and hydrophone). The system was evaluated for true positive, false positive, location accuracy and leak size threshold performance criteria at the test bed. The test bed results are summarized in Tables 6-6 and 6-7 for the accelerometers and hydrophones, respectively. For each sensor configuration, depictions of the projected and known leak locations are presented in Figures 6-6 to 6-9 for PVC and DI pipe materials. False positive data are presented in Tables 6-8 and 6-9. These results were compared to the performance criteria as part of the technology performance assessment.

Using accelerometer sensors, the LeakFinderRT system provided 100% reliability in providing leak detection (true positive) results for the controlled conditions of the test bed (see Table 6-6). Location results were suitably accurate as well. On the PVC section of the test bed, the LeakFinderRT system identified seven out of seven leaks within ± 4 ft. On the DI portion of the test bed, the system identified seven out of seven leaks within ± 4 ft. The LeakFinderRT system

with accelerometers was found to have a false positive rate at 33% and did not pass this criteria (see Table 6-8). However, the usual protocol would call for the operator to perform a focused follow-up inspection at the correlated leak location with the LeakTuner™ device, so it is possible this helps to minimize false positives during inspections conducted in the field. The system was found to be sensitive to detect leaks at approximately 1.0 gpm in both PVC and DI pipe. Overall, the LeakFinderRT system met the performance criteria thresholds for the test bed evaluation, except for the rate of false positives.

Using hydrophone sensors, the LeakFinderRT system had marginal success with a true positive rate of 86% with 12 out of 14 leaks detected (see Table 6-7). With hydrophone sensors, the system did not meet the location performance criterion for locating leaks with only seven out of 14 leaks located within ± 4 ft. The performance for the hydrophones was better on the PVC pipe with six out of seven leaks detected within ± 4 ft, while only one out of seven leaks was detected within ± 4 ft on the DI pipe. The hydrophone-equipped system also did not meet requirements for false positives, indicating leaks where none were present in two out of nine trials at a 22% rate (see Table 6-9). Again, false positives could be mitigated in the field with the follow-up LeakTuner™ verification that is typically performed by the operator when marking the suspected leak locations. The hydrophones were able to detect an approximately 1.0 gpm leak in DI pipe. Overall, the LeakFinderRT system with hydrophones did not meet the performance criteria thresholds for the test bed scenarios in this study.

### 6.3.2 Field Test Results

Field testing of the LeakFinderRT system was conducted from July 29 to 30, 2014. The sensor spacing is listed in Table 6-10. The total length of pipe surveyed was 2,360 ft of steel, PVC, and AC pipe. As summarized in Table 6-11, the field test detected one point of interest (POI) and one confirmed large leak both in the vicinity of Mississippi Road (Area B). There were no surface expression of leaks on the PVC and AC sections and no leaks were identified with LeakFinderRT.

Figure 6-10 shows the POI identified by the LeakFinderRT system, which was identified as a small leak. This was in the vicinity of the same valve where the ZoneScan Alpha had identified a leak, but located 76 ft southeast of the valve that is shown in Figure 6-5. There was no known water infrastructure in the immediate area, so the DPW decided not to excavate the POI for leak verification purposes.

Figure 6-11 shows the leak report for the confirmed large leak detected by the LeakFinderRT system and Figure 6-12 shows the corresponding acoustic leak signature. The facility excavated this leak location as shown in Figure 6-13 and significant water was observed within both excavations adjacent to the building. The DPW reported no visible rupture on the mainline and concluded that the leak was under the foundation. The DPW subsequently turned off the water to the building and plans to abandon the line under the foundation and install a new line.

The indication of two leaks in the field test did not provide sufficient information for evaluation of performance criteria for this portion of the work. In addition, the location of the leaks could

not be verified through excavation. One POI was not excavated and the other excavation for the large leak did not provide for verification of the leak location to compare to the system results.

**Table 6-6. Accelerometer Results Summary for LeakFinderRT Simulated Leak Testing**

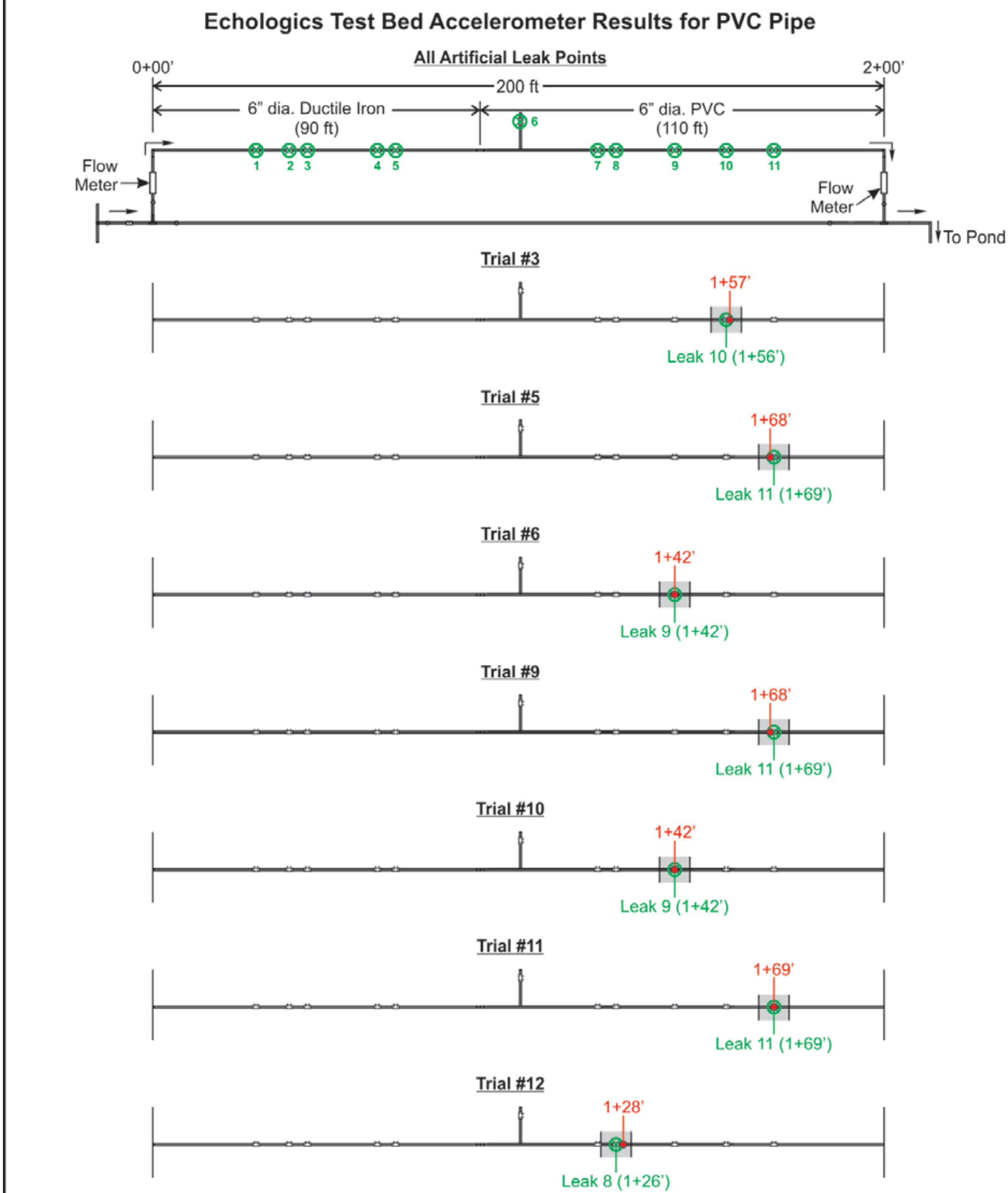
| Trial No. | Pipe Material | Leak No. | Distance to Leak[(a)] | Pressure | Estimated Leak Flow Rate[(b)] | Measured Leak Distance[(a)] | Accuracy | Within Performance Objective[(c)] |
|---|---|---|---|---|---|---|---|---|
| # | – | # | (ft) | (psi) | (gpm) | (ft) | (ft) | (Y/N) |
| 3 | PVC | 10 | 156 | 94 | 5.5 | 157 | 1 | Yes |
| 5 | PVC | 11 | 169 | 92 | 8.0 | 168 | 1 | Yes |
| 6 | PVC | 9 | 142 | 92 | 3.6 | 142 | 0 | Yes |
| 9* | PVC | 11 | 169 | 90 | 7.9 | 168 | 1 | Yes |
| 10* | PVC | 9 | 142 | 90 | 3.5 | 142 | 0 | Yes |
| 11* | PVC | 11 | 169 | 90 | 7.9 | 169 | 0 | Yes |
| 12 | PVC | 8 | 126 | 92 | 1.0 | 128 | 2 | Yes |
| 1 | DI | 2 | 37 | 94 | 5.5 | 34 | 3 | Yes |
| 2 | DI | 3 | 42 | 94 | 1.0 | 38 | 4 | Yes |
| 7 | DI | 4 | 61 | 90 | 3.5 | 58 | 3 | Yes |
| 9* | DI | 4 | 61 | 92 | 3.6 | 58 | 3 | Yes |
| 10* | DI | 2 | 37 | 92 | 5.4 | 34 | 3 | Yes |
| 11* | DI | 1 | 28 | 94 | 8.1 | 25 | 3 | Yes |
| 13 | DI | 1 | 28 | 94 | 8.1 | 25 | 3 | Yes |
| **Number of Leaks Detected** | | | | | | | **14/14** | **100%** |
| **Number of Correlated Distances within ± 4 ft (Overall)** | | | | | | | **14/14** | **100%** |
| **Number of Correlated Distances within ± 4 ft (PVC)** | | | | | | | **7/7** | **100%** |
| **Number of Correlated Distances within ± 4 ft (DI)** | | | | | | | **7/7** | **100%** |

(a) All distances are referenced from 0 ft
(b) Calculated using the pressure and Greely's formula
(c) Performance objective is ±4 ft of actual leak location

**Table 6-7. Hydrophone Results Summary for LeakFinderRT Simulated Leak Testing**

| Trial No. | Pipe Material | Leak No. | Distance to Leak[a] | Pressure | Estimated Leak Flow Rate[b] | Measured Leak Distance[a] | Accuracy | Within Performance Objective[c] |
|---|---|---|---|---|---|---|---|---|
| # | – | # | (ft) | (psi) | (gpm) | (ft) | (ft) | (Y/N) |
| 3 | PVC | 10 | 156 | 94 | 5.5 | 158 | 2 | Yes |
| 5 | PVC | 11 | 169 | 92 | 8.0 | 170 | 1 | Yes |
| 6 | PVC | 9 | 142 | 92 | 3.6 | 144 | 2 | Yes |
| 9* | PVC | 11 | 169 | 94 | 8.1 | 170 | 1 | Yes |
| 10* | PVC | 9 | 142 | 95 | 3.6 | 144 | 2 | Yes |
| 11* | PVC | 11 | 169 | 94 | 8.1 | 170 | 1 | Yes |
| 12 | PVC | 8 | 126 | 96 | 1.0 | OOBW | ND | No |
| 1 | DI | 2 | 37 | 92 | 5.4 | 33 | 4 | Yes |
| 2 | DI | 3 | 42 | 92 | 1.0 | 32 | 10 | No |
| 7 | DI | 4 | 61 | 94 | 3.6 | 52 | 9 | No |
| 9* | DI | 4 | 61 | 96 | 3.7 | 71 | 10 | No |
| 10* | DI | 2 | 37 | 94 | 5.5 | 75 | 38 | No |
| 11* | DI | 1 | 28 | 92 | 8.0 | OOBB | ND | No |
| 13 | DI | 1 | 28 | 92 | 8.0 | 13 | 15 | No |
| **Number of Leaks Detected** | | | | | | | **12/14** | **86%** |
| **Number of Correlated Distances within ± 4 ft (Overall)** | | | | | | | **7/14** | **50%** |
| **Number of Correlated Distances within ± 4 ft (PVC)** | | | | | | | **6/7** | **86%** |
| **Number of Correlated Distances within ± 4 ft (DI)** | | | | | | | **1/7** | **14%** |

ND = Leak not detected; OOBW = out of bracket white sensor; OOBB = out of bracket blue sensor
(a) All distances are referenced from 0ft
(b) Calculated using the pressure and Greely's formula
(c) Performance objective is ±4ft of actual leak location




Explanation

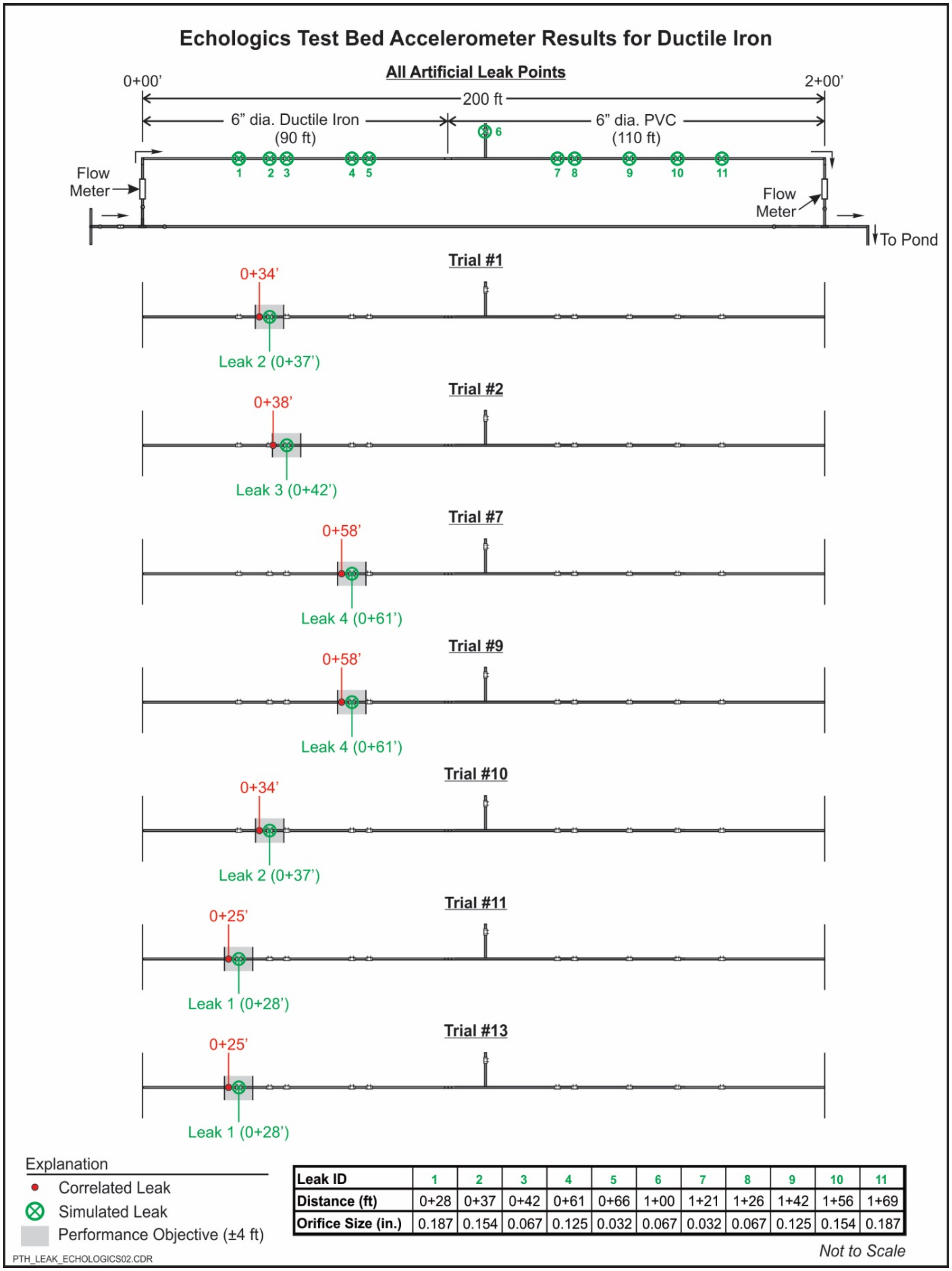
- Correlated Leak
- Simulated Leak
- Performance Objective (±4 ft)

| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

PTH_LEAK_ECHOLOGICS02.CDR

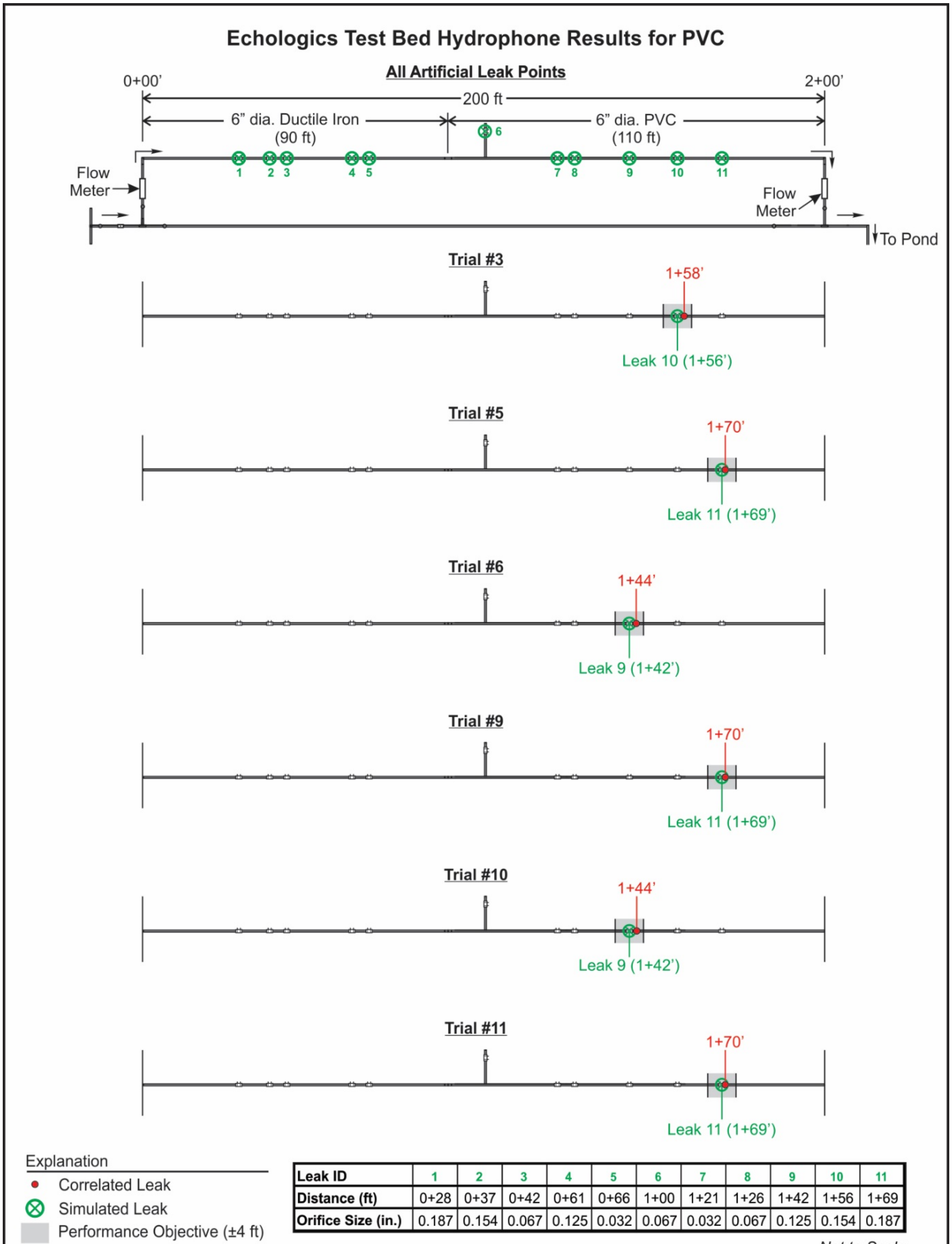
*Not to Scale*

**Figure 6-6. LeakFinderRT Simulated Leak Testing Results on PVC Pipe Using Accelerometer**




| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

**Figure 6-7. LeakFinderRT Simulated Leak Testing Results on DI Pipe Using Accelerometer**

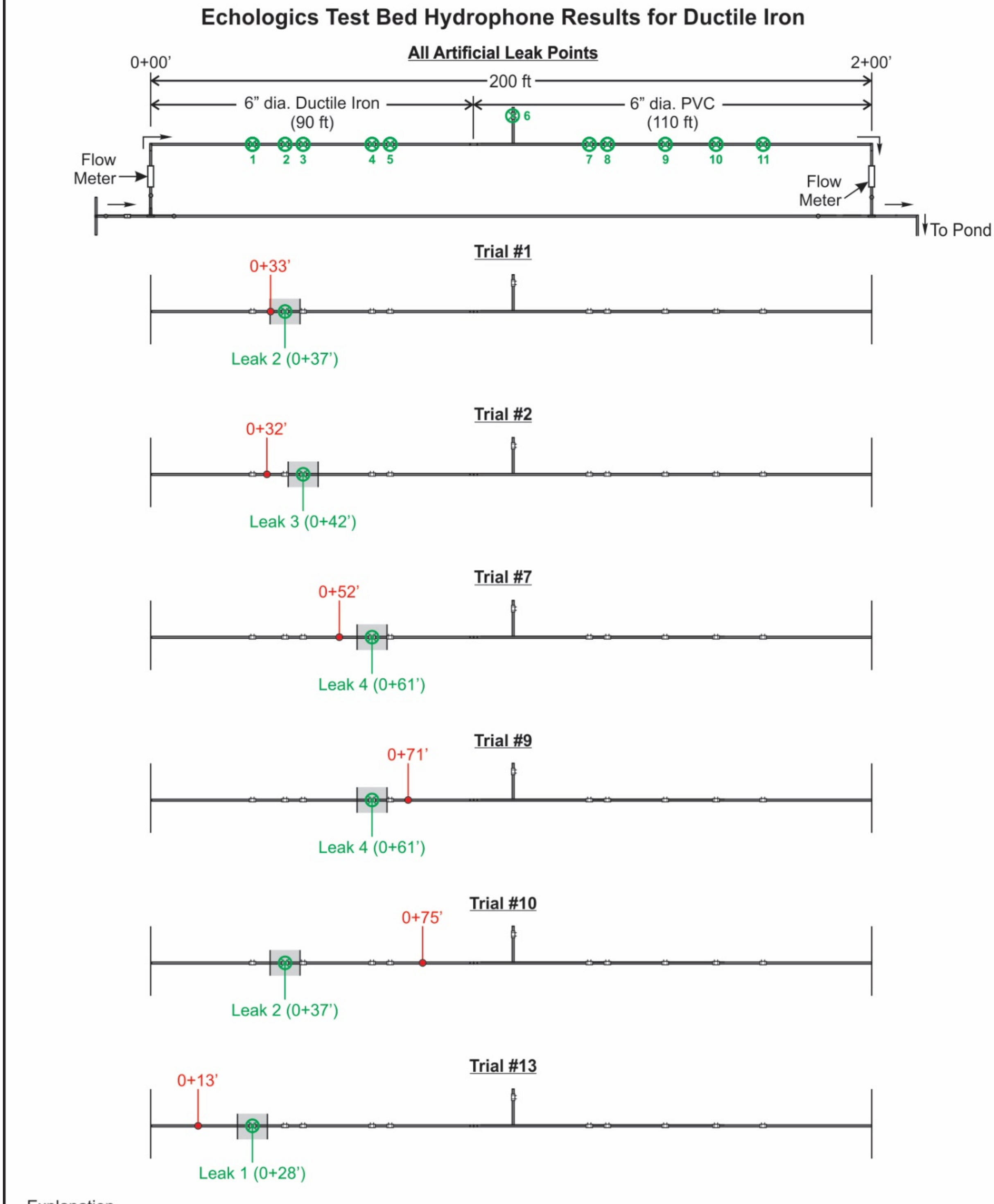



| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

PTH_LEAK_ECHOLOGICS02.CDR

*Not to Scale*

**Figure 6-8. LeakFinderRT Simulated Leak Testing Results on PVC Pipe Using Hydrophone**




| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+37 | 0+42 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

**Figure 6-9. LeakFinderRT Test Bed Results on DI Pipe Using Hydrophone**

**Table 6-8. False Positive Results for LeakFinderRT System with Accelerometers**

| Trial No. | Leak No. | Leak Location | DI Bracket Result[(a)] (ft) | PVC Bracket Result[(a)] (ft) | False Positive (Yes/No) |
|---|---|---|---|---|---|
| 1 | 2 | DI | 34 | OOBB | No |
| 2 | 3 | DI | 38 | 159 | Yes |
| 3 | 10 | PVC | OOBB | 157 | No |
| 4 | None | NA | OOBB | OOBW | No |
| 5 | 11 | PVC | OOBB | 168 | No |
| 6 | 9 | PVC | OOBB | 142 | No |
| 7 | 4 | DI | 58 | 178 | Yes |
| 12 | 8 | PVC | 60 | 128 | Yes |
| 13 | 1 | DI | 25 | OOBB | No |
| **Number of False Positives** | | | | **3/9** | **33%** |

OOBB = out of bracket blue sensor; NA = not available

[(a)]All distances are referenced from 0 ft

**Table 6-9. False Positive Results for LeakFinderRT System with Hydrophones**

| Trial No. | Leak No. | Leak Location | DI Bracket Correlation Result[(a)] (ft) | PVC Bracket Correlation Result[(a)] (ft) | False Positive (Yes/No) |
|---|---|---|---|---|---|
| 1 | 2 | DI | 33 | OOBW* | No |
| 2 | 3 | DI | 32 | OOBW* | No |
| 3 | 10 | PVC | 72 | 158 | Yes |
| 4 | None | NA | No Leak | OOBW* | No |
| 5 | 11 | PVC | No Leak | 170 | No |
| 6 | 9 | PVC | OOBB | 145 | No |
| 7 | 4 | DI | 52 | OOBW* | No |
| 12 | 8 | PVC | 67 | OOBW* | Yes |
| 13 | 1 | DI | 13 | OOBW* | No |
| **Number of False Positives** | | | | **2/9** | **22%** |

OOBB = out of bracket blue sensor; OOBW = out of bracket white sensor; NA = not available

[(a)]All distances are referenced from 0 ft

*No leak detected with the bracket portion of the test bed; possible leak noise outside of bracketed portion of test bed

**Table 6-10. Distribution Pipe at ERDC Surveyed by LeakFinderRT for Field Test**

| Segment | Site | Location | Sensor to Sensor Spacing (ft) | Material | Pipe Size (in) | Sensor Type |
|---|---|---|---|---|---|---|
| 1 | Area A | S1 to S2 | 675 | PVC, Steel | 6 | Hydrophone |
| 2 | Area A | S2 to S3 | 345 | Steel | 6 | Accelerometer |
| 3 | Area B | S6 to S7 | 270 | PVC | 6 | Accelerometer |
| 4 | Area B | S7 to S8 | 404 | Steel | 6 | Accelerometer |
| 5 | Area B | S8 to S9 | 375 | Steel | 6 | Accelerometer |
| 6 | N. Platte | Hydrant Valve to Gate Valve | 291 | AC | 6 | Accelerometer |
| | | **Total** | **2,360** | | | |

**Table 6-11. LeakFinderRT Field Survey on Distribution Pipe at ERDC**

| Item ID | Area | Leak or POI | Leak Type | Estimated Size | Site Address | Calculated Leak Size (gpm) |
|---|---|---|---|---|---|---|
| 1 | B | POI | Main | Small | 3281 Mississippi Rd. | 11.1 |
| 2 | B | Leak | Main | Large | 3281 Mississippi Rd. | 59.3 |

echologics

## Leakage Sheet

| | | | | | |
|---|---|---|---|---|---|
| Date | July 30, 2014 | Leak No | 1 | Crew | MA/KS |
| Address | 3281 MISSISSIPPI RD | | | | |
| Leak Code | WMLK | Leak Class | C | Leak Visible | No |
| Leak At | Main Leak | Est Water Loss in GPM | 11 | Map Area | Area B |
| Pipe Material | Steel | Pipe Size | 6 | GPSID | 1 |
| Latitude: | 32.1758318 | Longitude: | 90.5147414 | | |

Leak Photo

**Figure 6-10. LeakFinderRT Results for POI Identified at ERDC**

echologics

Leakage Sheet

| | | | | | |
|---|---|---|---|---|---|
| Date | July 30, 2014 | Leak No | 2 | Crew | MA/KS |
| Address | 3281 MISSISSIPPI RD | | | | |
| Leak Code | WMLK | Leak Class | B | Leak Visible | Yes |
| Leak At | Main Leak | Est Water Loss in GPM | 59 | Map Area | Area B |
| Pipe Material | CI | Pipe Size | 6 | GPSID | 2 |
| Latitude: | 32.1759883 | Longitude: | 90.5142515 | | |

Leak Photo

**Figure 6-11. LeakFinderRT Results for Large Leak Identified at ERDC**

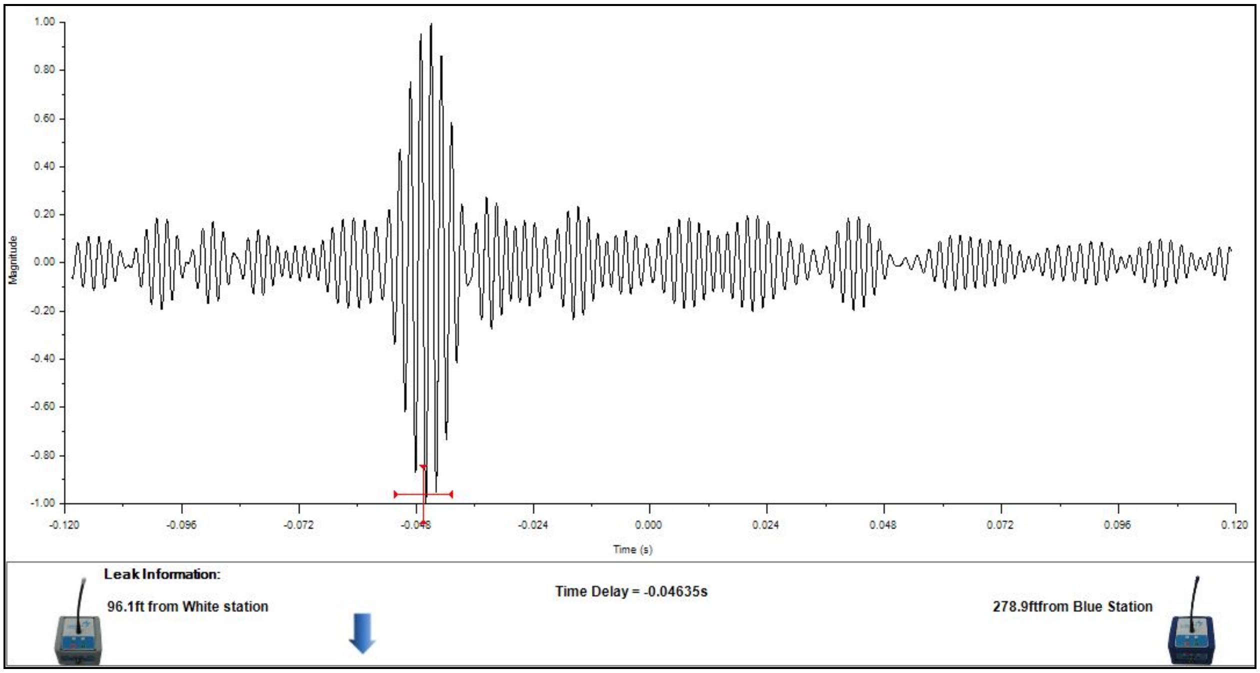



**Figure 6-12. LeakFinderRT Correlation Results for the Large Leak Identified at ERDC**

**Figure 6-13. Excavation of the Large Leak Identified at ERDC**

## 6.4 Correlux Test Evaluation

### 6.4.1 Test Bed Results

Testing of the Correlux leak detection system was performed from April 28 to April 29, 2015. The system was evaluated for true positive, false positive, location accuracy and leak size threshold performance criteria at the test bed. The test bed results are summarized in Table 6-12. Depictions of the projected and known leak locations are presented in Figures 6-14 and 6-15 for PVC and DI pipe materials, respectively. False positive data are presented in Table 6-13. These results were compared to the performance criteria as part of the technology performance assessment.

The Correlux system provided 100% reliability in providing leak detection (true positive) results for the controlled conditions of the test bed. Location results were suitably accurate as well with 93% of leaks detected within ± 4 ft. On the PVC section of the test bed, the Correlux system identified six out of seven leaks within ± 4 ft. On the DI portion of the test bed, the system identified seven out of seven leaks within ± 4 ft. The system had no false positive indications of leaks. The system was also found to be able to detect a simulated leak at approximately 1.1 gpm in DI pipe. The Correlux system was the only technology to meet all performance criteria threshold for the test bed scenarios in this study.

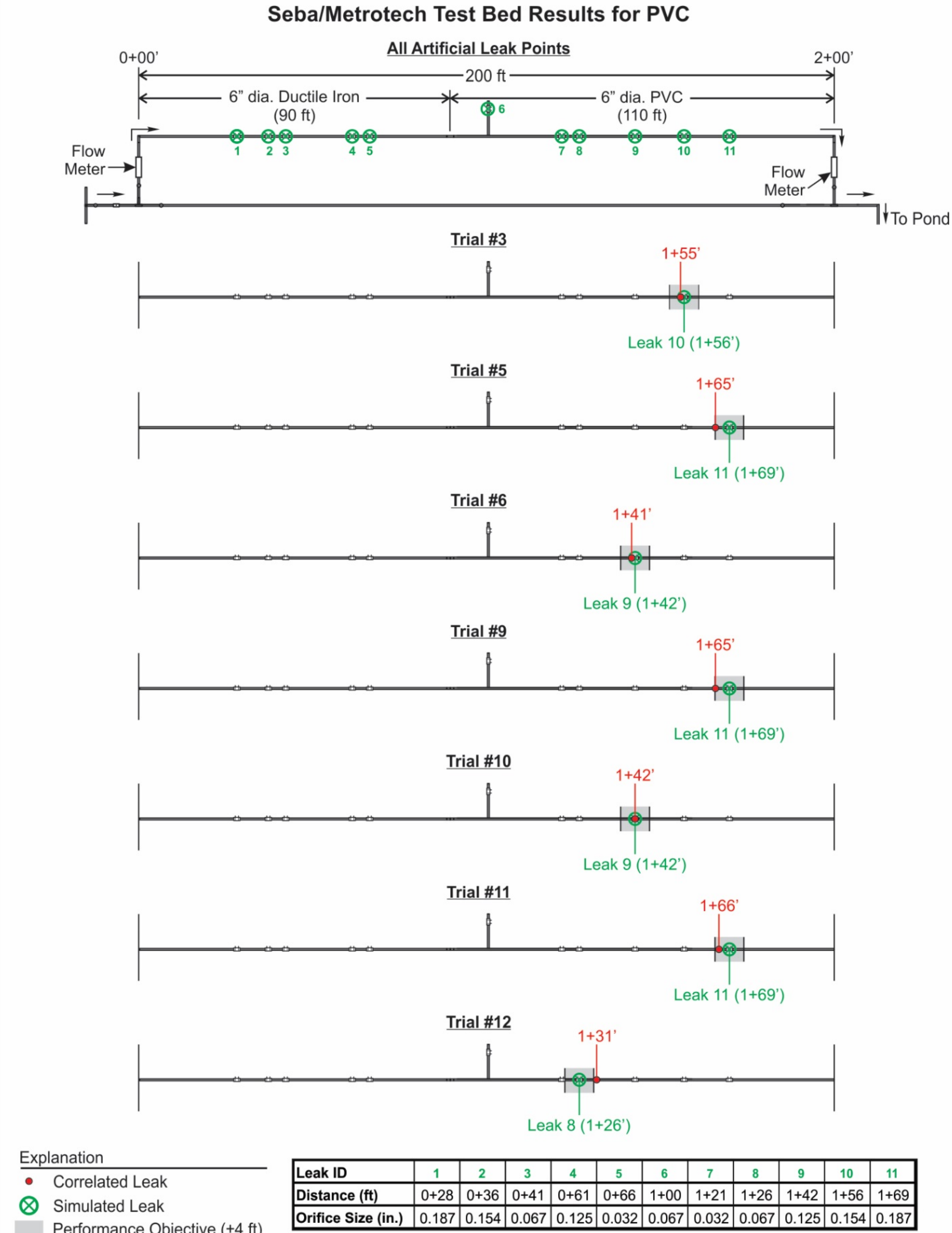
### 6.4.2 Field Test Results

The Correlux system was tested within the ERDC water distribution system on December 17, 2015. No leaks were found on 243 ft of PVC pipe inspected on Missouri Road (in the northeastern portion of the installation) or on 285 ft of AC pipe on N. Platte Road (in the southern portion of the installation). The other areas of the water distribution system inspected previously in 2014 by the other technologies were inaccessible due to ongoing construction. Because no leaks were identified, there was insufficient data to evaluate the performance criteria for this portion of the field demonstration. However, results were consistent with the other two technologies, which found no leaks in these specific areas of the ERDC water distribution system.

**Table 6-12. Summary of Test Bed Results for the Correlux System**

| Trial No. | Pipe Material | Leak No. | Distance to Leak[a] | Pressure | Estimated Leak Flow Rate[b] | Measured Leak Distance[a] | Accuracy | Within Performance Objective[c] |
|---|---|---|---|---|---|---|---|---|
| # | – | # | (ft) | (psi) | (gpm) | (ft) | (ft) | (Y/N) |
| 3 | PVC | 10 | 156 | 94 | 5.5 | 155 | 1 | Yes |
| 5 | PVC | 11 | 169 | 92 | 8.0 | 165 | 4 | Yes |
| 6 | PVC | 9 | 142 | 94 | 3.6 | 141 | 1 | Yes |
| 9* | PVC | 11 | 169 | 98 | 8.3 | 165 | 4 | Yes |
| 10* | PVC | 9 | 142 | 98 | 3.7 | 142 | 0 | Yes |
| 11* | PVC | 11 | 169 | 96 | 8.2 | 166 | 3 | Yes |
| 12 | PVC | 8 | 126 | 92 | 1.0 | 131 | 5 | No |
| 1 | DI | 2 | 37 | 97 | 5.6 | 33 | 4 | Yes |
| 2 | DI | 3 | 42 | 97 | 1.1 | 43 | 1 | Yes |
| 7 | DI | 4 | 61 | 90 | 3.5 | 58 | 3 | Yes |
| 9* | DI | 4 | 61 | 97 | 3.7 | 59 | 2 | Yes |
| 10* | DI | 2 | 37 | 97 | 5.6 | 36 | 1 | Yes |
| 11* | DI | 1 | 28 | 97 | 8.2 | 28 | 0 | Yes |
| 13 | DI | 1 | 28 | 97 | 8.2 | 30 | 2 | Yes |
| **Number of Leaks Detected** | | | | | | | **14/14** | **100%** |
| **Number of Correlated Distances within ± 4 ft (Overall)** | | | | | | | **13/14** | **93%** |
| **Number of Correlated Distances within ± 4 ft (PVC)** | | | | | | | **6/7** | **86%** |
| **Number of Correlated Distances within ± 4 ft (DI)** | | | | | | | **7/7** | **100%** |

(a) All distances are referenced from 0 ft
(b) Calculated using pressure and Greely's formula
(c) Performance objective is ±4 ft of actual leak location
* Trial conducted with two leaks turned on; one on each pipe material.

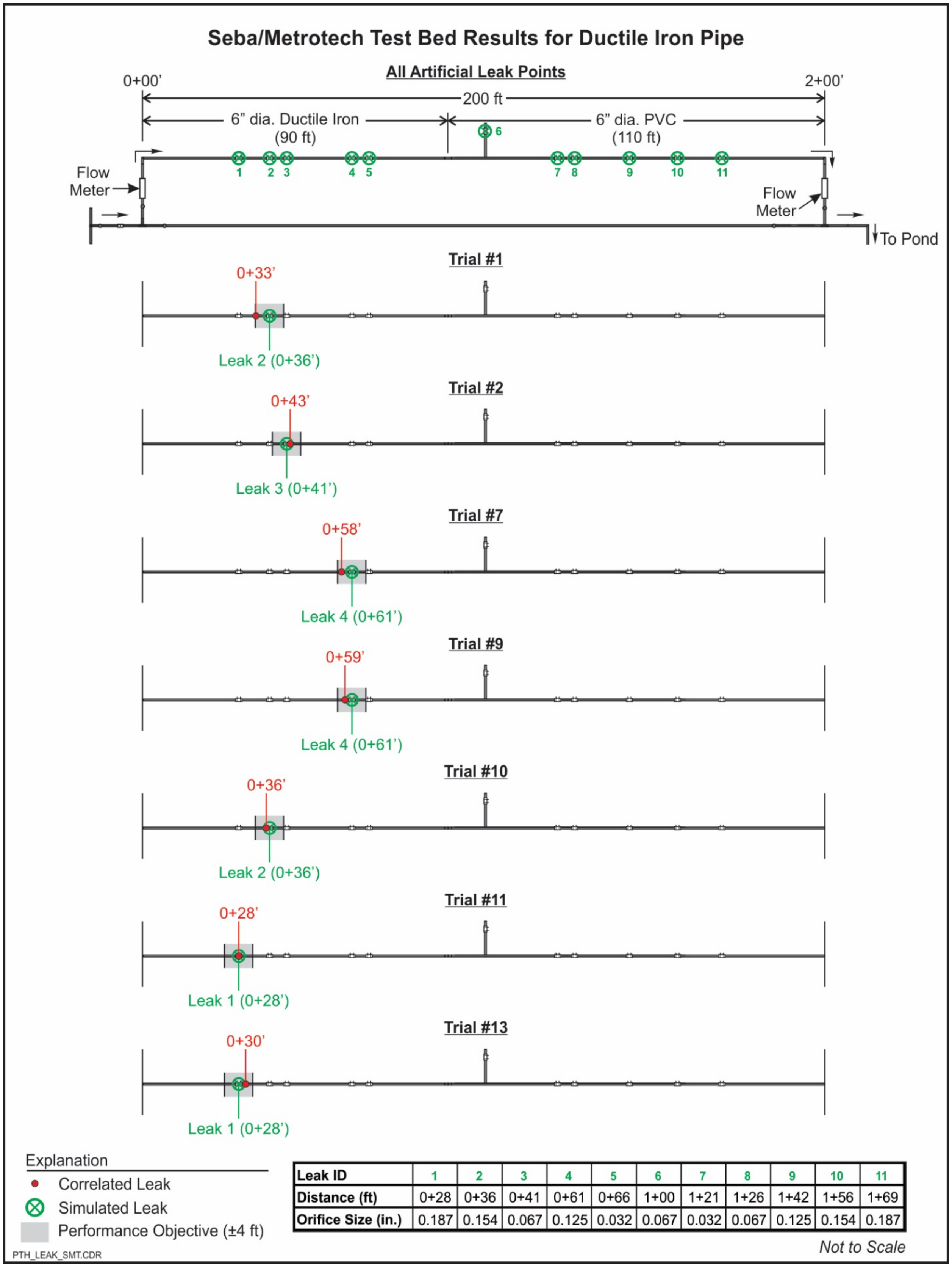



| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+36 | 0+41 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

PTH_LEAK_SMT.CDR

*Not to Scale*

**Figure 6-14. Correlux System Simulated Leak Testing Results on PVC Pipe**




| Leak ID | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance (ft) | 0+28 | 0+36 | 0+41 | 0+61 | 0+66 | 1+00 | 1+21 | 1+26 | 1+42 | 1+56 | 1+69 |
| Orifice Size (in.) | 0.187 | 0.154 | 0.067 | 0.125 | 0.032 | 0.067 | 0.032 | 0.067 | 0.125 | 0.154 | 0.187 |

**Figure 6-15. Correlux System Simulated Leak Testing Results on DI Pipe**

**Table 6-13. Summary of False Positive Results for Correlux System**

| Trial No. | Leak No. | Leak Location | DI Bracket Result[a] (ft) | PVC Bracket Result[a] (ft) | False Positive (Yes/No) |
|---|---|---|---|---|---|
| 1 | 2 | DI | 33 | OOB | No |
| 2 | 3 | DI | 43 | OOB | No |
| 3 | 10 | PVC | OOB | 155 | No |
| 4 | None | NA | No Leak | No Leak | No |
| 5 | 11 | PVC | OOB | 165 | No |
| 6 | 9 | PVC | OOB | 141 | No |
| 7 | 4 | DI | 58 | OOB | No |
| 12 | 8 | PVC | OOB | 131 | No |
| 13 | 1 | DI | 30 | OOB | No |
| **Number of False Positives** | | | | **0/9** | **0.0%** |

OOBB = out of bracket blue sensor; NA = not available

[a]All distances are referenced from 0 ft

## 6.5 Supplemental Leak Detection Studies

Supplemental leak trials were performed to further test the capabilities of the innovative acoustic leak detection systems. This involved the following additional simulated leak scenarios for the ZoneScan Alpha and/or Correlux technologies:

- Bracketing multiple pipe types and multiple leaks;
- Testing on a longer run of PVC pipe at 205 feet in total length; and
- Testing on the PVC lateral located off of the main test bed.

These supplemental trials were used to test the limits of leak detection technology performance. However, these trials were not included in the original performance criteria for the study, so are provided here for informational purposes.

As shown in Table 6-14, three separate trials were conducted for each technology with two simulated leaks running at the same time on the test bed. All leaks were spaced more than 5 ft apart. All three technologies were tested under this multiple leak scenario with the sensor pair bracketing both the DI and PVC pipe. The leak detection and location accuracy was reduced under this scenario with multiple leaks running and sensors bracketing multiple pipe types. In all cases, only one of the two simulated leaks was detected. In all trials, where a detection occurred it was the PVC leak that was detected. None of the ductile iron leaks were detected. This may be due to the large flow rate of the PVC leaks relative to the DI leaks during Trials 9 and 10. For Trial 11, the flow rates were equal and the leaks on the DI and PVC pipes about equidistant from the sensors on either end of the test bed. For Trial 11, no leaks were detected by the ZoneScan Alpha and Correlux units. For Trial 11, only the PVC leak was detected by the LeakFinderRT in the accelerometer and hydrophone configuration. The ability to detect and accurately locate two or more leaks may require further investigation based upon these preliminary field trials.

**Table 6-14. Multiple Leak Trial Comparison**

| Trial No. | Pipe Material | Leak No. | Distance to Leaks | Measured Leak Flow Rate[a] | Correlated Leak Distance | Accuracy | Within Performance Objective[(c)] |
|---|---|---|---|---|---|---|---|
| # | – | # | (ft) | (gpm) | (ft) | (ft) | (Y/N) |
| **ZoneScan Alpha Multiple Leak Trials** | | | | | | | |
| 9 | Mixed | 4, 11 | 61, 169 | 1, 6 | 172 | 3 (PVC) | No DI; Yes PVC |
| 10 | Mixed | 2, 9 | 36, 142 | 4, 20[b] | 139 | 3 (PVC) | No DI; Yes PVC |
| 11 | Mixed | 1, 11 | 28, 169 | 6, 6 | 190 | 21 (PVC) | No DI; No PVC |
| **LeakFinderRT Accelerometer Multiple Leak Trials** | | | | | | | |
| 9 | Mixed | 4, 11 | 61, 169 | 1, 6 | 168 | 1 (PVC) | No DI; Yes PVC |
| 10 | Mixed | 2, 9 | 36, 142 | 4, 20[b] | 142 | 0 (PVC) | No DI; Yes PVC |
| 11 | Mixed | 1, 11 | 28, 169 | 6, 6 | 169 | 0 (PVC) | No DI; Yes PVC |
| **LeakFinderRT Hydrophone Multiple Leak Trials** | | | | | | | |
| 9 | Mixed | 4, 11 | 61, 169 | 1, 6 | 170 | 1 (PVC) | No DI; Yes PVC |
| 10 | Mixed | 2, 9 | 36, 142 | 4, 20[b] | 144 | 2 (PVC) | No DI; Yes PVC |
| 11 | Mixed | 1, 11 | 28, 169 | 6, 6 | 170 | 1 (PVC) | No DI; Yes PVC |
| **Correlux Multiple Leak Trials** | | | | | | | |
| 9 | Mixed | 4, 11 | 61, 169 | 1, 6 | 164 | 5 (PVC) | No DI; No PVC |
| 10 | Mixed | 2, 9 | 36, 142 | 4, 20[b] | 140 | 2 (PVC) | No DI; Yes PVC |
| 11 | Mixed | 1, 11 | 28, 169 | 6, 6 | 130 | 39 (PVC) | No DI; No PVC |

(a) Measured flow rate as measured in July 2015
(b) Estimated flow rate based on orifice defect size

As shown in Tables 6-15 and 6-16, two of the technologies tested were not able to detect leaks within the ± 4 ft leak location specification at the longer sensor separation of 205 ft on 6-inch PVC pipe. The lower end of the manufacturer specified limits for sensor spacing on PVC pipe were 200 to 300 ft with some allowance for spacing up to 250 to 500 ft (see Section 2). These results suggest that it would be prudent to stay within the lower end of the spacing guidelines for PVC pipe inspections. However, further testing may be warranted based upon these preliminary test results due to the limited number of trials involved.

As shown in Tables 6-17 and 6-18, the acoustic noise signals from simulated leaks on the PVC service lateral located off of the main test bed were able to be detected within a range of sizes from 1 to 8 gpm. However, the overall the leak location was not accurate to the ± 4 ft criterion. This suggests that the detection of leaks on service laterals may be challenging. Some AMI systems are equipped with separate noise loggers associated with the water meter and service line, which could provide supplemental coverage for leak detection on these smaller pipes located off of the main grid.

**Table 6-15. ZoneScan Alpha Leak Detection and Location Trials on Long PVC Run**

| Trial No. | Leak Size | Distance to Leak | Estimated Leak Flow Rate[a] | Correlated Leak Distance[b] | Accuracy | Within Performance Objective |
|---|---|---|---|---|---|---|
| # | # | (ft) | (gpm) | (ft) | (ft) | (Y/N) |
| **1** | 0.067 | 43 | 1.0 | 167.7 | 124.7 | No |
| **2** | 0.0935 | 43 | 2.0 | 94.1 | 51.1 | No |
| **3** | 0.125 | 43 | 3.6 | 125.1 | 82.1 | No |
| **4** | 0.154 | 43 | 5.4 | Data Error | N/A | N/A |
| **5** | 0.187 | 43 | 8.0 | 95.7 | 52.7 | No |
| **ZoneScan Alpha Number of Leaks Detected** | | | | | **4/4 (100%)** | **Yes** |
| **ZoneScan Alpha Correlated Distances within ± 4 ft** | | | | | **0/4 (0%)** | **No** |

(a) Based on pressure and Greely's formula
(b) Distance from Sensor B (East) located closest to the simulated leak

**Table 6-16. Correlux Leak Detection and Location Trials on Long PVC Run**

| Trial No. | Leak Size | Distance to Leak | Estimated Leak Flow Rate[a] | Correlated Leak Distance[b] | Accuracy | Within Performance Objective |
|---|---|---|---|---|---|---|
| # | # | (ft) | (gpm) | (ft) | (ft) | (Y/N) |
| 1 | 0.067 | 43 | 1.0 | ND | ND | No |
| 2 | 0.0935 | 43 | 2.1 | ND | ND | No |
| 3 | 0.125 | 43 | 3.6 | 60.5 | 17.5 | No |
| 4 | 0.154 | 43 | 5.5 | 149 | 106 | No |
| 5 | 0.187 | 43 | 8.0 | 45 | 2 | Yes |
| **Correlux Number of Leaks Detected** | | | | | **3/5 (60%)** | **No** |
| **Correlux No. of Correlated Distances within ± 4 ft** | | | | | **1/5 (20%)** | **No** |

(a) Based on pressure and Greely's formula
(b) Distance from Sensor B (East) located closest to the simulated leak

**Table 6-17. ZoneScan Alpha Leak Detection and Location Trials on a Lateral**

| Trial No. | Leak Size | Distance to Leak | Estimated Leak Flow Rate[a] | Correlated Leak Distance[b] | Accuracy | Within Performance Objective |
|---|---|---|---|---|---|---|
| # | # | (ft) | (gpm) | (ft) | (ft) | (Y/N) |
| 1 | 0.067 | 10 | 1.0 | 40 | 30 | No |
| 2 | 0.0935 | 10 | 2.0 | 145 | 135 | No |
| 3 | 0.125 | 10 | 3.5 | 91 | 81 | No |
| 4 | 0.154 | 10 | 5.3 | 9 | 1 | Yes |
| 5 | 0.187 | 10 | 7.7 | 23 | 13 | No |
| **ZoneScan Alpha Number of Leaks Detected** | | | | | **5/5 (100%)** | **Yes** |
| **ZoneScan Alpha No. of Correlated Distances within ± 4 ft** | | | | | **1/5 (20%)** | **No** |

a) Based on pressure and Greely's formula
b) Distance from sensor on center riser located closest to the simulated leak

**Table 6-18. Correlux Leak Detection and Location Trials on a Lateral**

| Trial No. | Leak Size | Distance to Leak | Estimated Leak Flow Rate[a] | Correlated Leak Distance[b] | Accuracy | Within Performance Objective |
|---|---|---|---|---|---|---|
| # | # | (ft) | (gpm) | (ft) | (ft) | (Y/N) |
| 1 | 0.067 | 10 | 1.0 | 14 | 4 | Yes |
| 2 | 0.0935 | 10 | 2.0 | 14 | 4 | Yes |
| 3 | 0.125 | 10 | 3.6 | No Leak Detected | N/A | No |
| 4 | 0.154 | 10 | 5.5 | 83 | 73 | No |
| 5 | 0.187 | 10 | 8.2 | 14 | 4 | Yes |
| **Correlux Number of Leaks Detected** | | | | | **4/5 (80%)** | **No** |
| **Correlux No. of Correlated Distances within ± 4 ft** | | | | | **3/5 (60%)** | **No** |

(a) Based on pressure and Greely's formula
(b) Distance from sensor on center riser located closest to the simulated leak

# 7.0 COST ASSESSMENT

The cost models developed for this demonstration serve as a means to evaluate the expected life cycle costs for the use of innovative acoustic leak detection systems. The life-cycle cost estimates are calculated for operating in either a continuous monitoring mode or through periodic inspections. Water savings, energy savings, and SIR values for leak detection were estimated based upon typical breakage frequency per mile and assumptions about potential rates of water loss. Although the leak inspections conducted as part of this demonstration revealed potential losses of up to 37 million gallons per year, an insufficient number of leaks could be excavated and/or verified from the field tests to assess likely rates of water loss within the entire ERDC water distribution system. Therefore, industry data and other historical information provided the basis for the life cycle cost estimates as summarized below. The SIR estimates suggest that there can be a positive cost outcome for use of these innovative leak detection technologies depending on the level of water loss within the water distribution system.

## 7.1 Cost Models

The life cycle costs were estimated over a 15-year period for all three technologies. Because the ZoneScan Alpha system is permanently installed on base, while the LeakFinderRT and Correlux systems are contracted services, the timeframe under consideration required normalization for comparison. The sensors and transmitters in the ZoneScan Alpha system are expected to last 15 years on site, so this was selected as the total life cycle timeframe. According to *AWWA Manual of Water Supply Practices M36: Water Audits and Loss Control Programs* (2009), leak detection surveys should be conducted every three years. Therefore, it was assumed that the LeakFinderRT or Correlux surveys would be performed at baseline and then every three years up to 15 total years (e.g., years 0, 3, 6, 9, 12, and 15). Note that the economic payback period for these technologies could be significantly shorter if a large number of leaks or high volume leaks are located. According to the National Institute of Standards and Technology (NIST) *Annual Supplement to NIST Handbook 135: Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis* (2015), the implied long-term average rate of inflation is only 0.1%, so inflation was not taken into account in the calculations below. A discount rate of 3% was used for the net present value (NPV) calculations as required for energy and water projects for Federal agencies (NIST, 2015).

The same water loss assumptions were used for each cost model. These are estimated values because the exact leakage rate within the ERDC water distribution system could not be established. As shown in Table 7-1, it is estimated that there would be 3.1 leaks at ERDC per year based on the size of its water distribution system, which would result in over 46 leaks in 15 years. Without leak detection efforts, the total water loss was assumed to be approximately 194 million gallons over 15 years based upon the typical breakage frequency of 0.25 breaks per mile per year (WaterRF, 2015) and a minimum detectable leak size of 1 gpm as identified from the demonstration results. Normalizing this to an annual basis would be an average water loss of approximately 13 million gallons per year. This is well below the high value of 37 million gallons of annual water loss estimated from the LeakFinderRT survey performed in 2014 as described in Section 6. With continuous leak monitoring efforts on a daily basis, it is assumed that the full amount of water and energy conservation would be realized from avoiding this water loss due to leakage. Therefore, the savings from 194 million gallons of conserved water is valued

at approximately $560,119 over 15 years. Using an NPV calculation, the current value of the water and energy savings would be approximately $415,133 with a continuous monitoring scenario for leak detection.

With periodic inspections conducted every three years, some water loss would not be avoided during the time intervals between inspections. For example, a three-year leak inspection interval would result in a cumulative 9.7 million gallons of water lost from three leaks running for 3 years, three leaks running for 2 years, and three leaks running for 1 year undetected until the next inspection interval (see Table 7-1). The amount of this lost water over the inspection intervals was subtracted out to arrive at a net water volume conserved of approximately 146 million gallons with periodic inspections. With inspections every 3 years, the value of the water and energy savings would be reduced by 25% to approximately $420,089 over 15 years. Using an NPV calculation, the current value of the water and energy savings would be $304,786 with periodic inspection for leak detection.

**Table 7-1. Life Cycle Water Loss Estimated for ERDC Water Distribution System**

| **Water Loss Estimate Assumptions** | **Data** |
|---|---|
| ERDC Water Cost (per 1,000 Gallon) | $2.80 |
| ERDC Electrical Cost (per kW-hr) | $0.08 |
| ERDC Water Distribution Size (ft) | 65,000 |
| Leak Frequency (leaks per mile per year) | 0.25 |
| Total Number of Leaks Each Year | 3.1 |
| Total Number of Leaks in Life Cycle | 46 |
| Assumed Leak Size (gpm) | 1.0 |
| Life Cycle Period (years) | 15 |
| Leak Inspection Interval (years) | 3 |
| **Water Loss Volumes and Cost Savings Estimates** | **Results** |
| Estimated Life Cycle Water Conservation (gal) | 194,113,636 |
| Estimated Water Loss During Each Inspection Interval (gal) | 9,705,682 |
| Estimated Net Water Conservation with Periodic Inspection (gal) | 145,585,227 |
| Estimated Water Savings with Continuous Monitoring | $543,518 |
| Estimated Water Savings with Periodic Inspection | $407,639 |
| Estimated Total Energy Life Cycle Conservation (kWh) | 211,477 |
| Estimated Net Energy Savings with Periodic Inspection (kWh) | 158,608 |
| Estimated Energy Savings with Continuous Monitoring | $16,601 |
| Estimated Energy Savings with Periodic Inspection | $12,451 |
| Total Value of Savings with Continuous Monitoring | **$560,119** |
| Total Value of Savings with Periodic Inspection | **$420,089** |
| Discount Rate (NIST, 2015) | **3%** |
| NPV of Savings with Continuous Monitoring | **$415,133** |
| NPV of Savings with Periodic Inspection | **$304,786** |

Sections 7.1.1 to 7.1.3 provide the SIR estimates based on these water and energy savings compared to the technology implementation costs. Since relatively conservative assumptions were made regarding the annual rate of water leakage, then a high SIR value would be a good indication of the cost-effectiveness of employing these technologies nationwide. Local repair costs could not be established during the demonstration as no leaks were excavated and repaired. Typical leak repair costs are approximately $900 to $5,000 each for small diameter water mains (PNNL, 2013b, Grigg, 2007) . The repair costs are not included in the SIR estimates as these costs are incurred when leaks are found, whether the leaks are detected through monitoring or eventually discovered through surface expression. While the leaks may increase when allowed to persist for longer periods before discovery and repair, the repair costs should be essentially the same. There may be additional cost savings in cases where leak detection leads to repair before water from leaks causes damage to other infrastructure or buildings. However, these damages would only occur in limited situations, and the impacts would be highly variable. Exclusion of these cost savings from the cost benefit analysis means the SIR values provided are a more conservative estimate. While leaks may start slowly with gradually increasing leak rates, or may result from more instantaneous breaching of pipes or fittings (such as cracking of a pipe during a freeze event), the cost models assume average frequencies of leaks and average water loss rates for determination of costs and benefits of leak detection and repair.

### 7.1.1 ZoneScan Alpha Life Cycle Cost Estimate

The life cycle cost estimate and SIR for the ZoneScan Alpha system are summarized in Table 7-2. The capital costs include the purchase of the loggers and other hardware components as described in Section 2. Installation, set-up assistance, and software training are included in the capital cost. The O&M costs include primarily monthly data storage fees and battery replacement every five years. After the system is installed under guidance by the manufacturer, the local DPW personnel are responsible to monitor for leaks and to ensure that the system is running properly. The maximum water savings are realized with daily, continuous monitoring of the leak detection system. The SIR of 1.66 suggests a positive cost savings scenario for this technology.

**Table 7-2. Cost Summary for ZoneScan Alpha**

| ZoneScan Alpha Leak Detection Cost Estimate | Data |
|---|---|
| ERDC Water Distribution System (ft) | 65,000 |
| ERDC Water Distribution Metallic Pipe (ft) | 42,000 |
| ERDC Water Distribution Other Pipe (ft) | 23,000 |
| Number of Loggers | 150 |
| Capital Cost of Equipment | $130,000 |
| Annual O&M Cost | $2,700 |
| Labor Cost | $20.06 |
| Total Labor Per Day (hours) | 1 |
| Monitoring Cost (per day) | $20 |
| Total Duration of Monitoring (days per year) | 365 |
| Monitoring Coverage Per Event | 100% |

**Table 7-2. Cost Summary for ZoneScan Alpha (Continued)**

| ZoneScan Alpha Leak Detection Cost Estimate | Data |
|---|---|
| Life Cycle Period (years) | 15 |
| Total Number of Monitoring Events | 5,475 |
| Total Labor Cost for Annual Monitoring | $7,322 |
| **Total Life Cycle Cost** | **$280,329** |
| **NIST Discount Rate** | **3%** |
| **NPV Savings with Continuous Monitoring** | **$415,133** |
| **NPV Investment for Continuous Monitoring** | **$249,641** |
| **SIR** | **1.66** |

### 7.1.2 LeakFinderRT Life Cycle Cost Estimate

The life cycle cost estimate and SIR for the LeakFinderRT system are summarized in Table 7-3. In this case, the cost is a fee-for-service model for a one-time inspection versus purchasing the equipment for long-term use. The vendor costs include project planning, mobilization, field testing, analysis, and reporting. The total water and energy savings are reduced by about 25% under this scenario assuming an inspection interval of every 3 years over the 15-year life cycle timeframe. The SIR for this technology is less than one under the conservative assumptions made of a 1 gpm leak rate (e.g., the minimum detectable level). The SIR value could be positive if the typical leakage level in the system rose to 2.3 gpm on average with three breaks per year. This would be equivalent to a water loss at 446 million gallons over 15 years or 30 million gallons on average each year. This value is below the 37 million gallons of annual water loss identified in the LeakFinderRT survey in 2014 conducted under this demonstration for a select portion of the ERDC water distribution system. This suggests that a SIR value above one is possible for this technology depending on the level of water leakage within the water distribution system.

**Table 7-3. Cost Summary for LeakFinderRT**

| LeakFinderRT Leak Detection Cost Estimate | Data |
|---|---|
| ERDC Water Distribution Size (ft) | 65,000 |
| Inspection Rate (ft/day) | 5,000 |
| Total Duration of Inspection (days) | 13 |
| Inspection Cost (Per Day) | $10,647 |
| Inspection Coverage Per Event | 100% |
| Inspection Interval (Years) | 3 |
| Life Cycle Period | 15 |
| Total Number of Inspection Events | 6 |
| Total Cost Per Inspection Event | $138,411 |
| **Total Life Cycle Cost** | **$830,466** |
| **NIST Discount Rate** | **3%** |
| **NPV Savings with Periodic Inspection** | **$304,786** |
| **NPV Investment for Periodic Inspection** | **$672,994** |
| **SIR** | **0.45** |

### 7.1.3 Correlux Life Cycle Cost Estimate

The life cycle cost estimates and SIR values for the Correlux system are summarized in Tables 7-4, 7-5 and 7-6. In this case, two scenarios were estimated including a fee-for-service model versus purchasing the equipment for in-house use by DPW personnel. For periodic inspections, the vendor costs include project planning, mobilization, and field testing. The total water and energy savings are reduced by about 25% under this scenario assuming an inspection interval of every 3 years over the 15-year life cycle timeframe. The SIR of 2.10 suggests a positive cost savings scenario for this technology using a fee-for-service model. The purchase of the equipment with a SIR of 5.43 is even more cost effective, but would place the burden of accurate leak detection and time on the DPW staff. Table 7.6 shows the SIR sensitivity for this scenario under varying hourly labor to water cost rates.

**Table 7-4. Cost Summary for Correlux Contracted as Periodic Inspection Service**

| Correlux Leak Detection Cost Estimate | Data |
|---|---|
| ERDC Water Distribution Size (ft) | 65,000 |
| Inspection Rate (ft/day) | 3,750 |
| Total Duration of Inspection (days) | 17 |
| Inspection Cost Per Day | $1,725 |
| Inspection Coverage Per Event | 100% |
| Inspection Interval (years) | 3 |
| Life Cycle Period | 15 |
| Total Number of Inspection Events | 6 |
| Total Cost Per Inspection Event | $29,900 |
| **Total Life Cycle Cost** | **$179,400** |
| **Discount Rate** | **3%** |
| **NPV Savings with Periodic Inspection** | **$304,786** |
| **NPV Investment for Periodic Inspection** | **$145,382** |
| **SIR** | **2.10** |

**Table 7-5. Cost Summary for Correlux Purchased for Periodic Inspections**

| Correlux Leak Detection Cost Estimate | Data |
|---|---|
| ERDC Water Distribution System (ft) | 65,000 |
| Inspection Rate (ft/day) | 3,750 |
| Total Duration of Inspection (days) | 17 |
| Capital Cost of Equipment | $22,295 |
| Labor Cost | $20.06 |
| Crew Size | 2 |
| Inspection Cost (Per Day) | $401 |
| Inspection Coverage Per Event | 100% |
| Inspection Interval (Years) | 3 |

| Correlux Leak Detection Cost Estimate | Data |
|---|---|
| Life Cycle Period | 15 |
| Total Number of Inspection Events | 6 |
| Total Labor Cost Per Inspection Event | $6,954 |
| **Total Life Cycle Cost** | **$64,020** |
| **Discount Rate** | **3%** |
| **NPV Savings with Periodic Inspection** | **$304,786** |
| **NPV Investment for Equipment and Inspections** | **$56,108** |
| **SIR** | **5.43** |

**Table 7-6. SIRs for Various Labor and Water Cost (for Correlux Purchased Scenario)**

| SebaKMT Correlux Purchase Labor Costs (per Hour) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Water Cost (per 1000 gal)** | $20.00 | $25.00 | $30.00 | $35.00 | $40.00 | $45.00 | $50.00 | $55.00 | $60.00 | $65.00 |
| | **Savings to Investment Ratio (SIR)** | | | | | | | | | |
| $0.50 | 1.10 | 0.96 | 0.85 | 0.76 | 0.69 | 0.63 | 0.58 | 0.54 | 0.50 | 0.47 |
| $1.50 | 2.99 | 2.60 | 2.30 | 2.06 | 1.87 | 1.71 | 1.57 | 1.46 | 1.36 | 1.27 |
| $2.50 | 4.88 | 4.24 | 3.75 | 3.36 | 3.04 | 2.78 | 2.56 | 2.37 | 2.21 | 2.07 |
| $3.50 | 6.76 | 5.88 | 5.20 | 4.66 | 4.22 | 3.86 | 3.55 | 3.29 | 3.07 | 2.87 |
| $4.50 | 8.65 | 7.52 | 6.65 | 5.96 | 5.40 | 4.93 | 4.54 | 4.21 | 3.92 | 3.67 |
| $5.50 | 10.53 | 9.16 | 8.10 | 7.26 | 6.58 | 6.01 | 5.54 | 5.13 | 4.78 | 4.47 |
| $6.50 | 12.42 | 10.80 | 9.55 | 8.56 | 7.75 | 7.09 | 6.53 | 6.05 | 5.64 | 5.28 |
| $7.50 | 14.31 | 12.43 | 11.00 | 9.86 | 8.93 | 8.16 | 7.52 | 6.97 | 6.49 | 6.08 |
| $8.50 | 16.19 | 14.07 | 12.45 | 11.16 | 10.11 | 9.24 | 8.51 | 7.89 | 7.35 | 6.88 |
| $9.50 | 18.08 | 15.71 | 13.90 | 12.46 | 11.29 | 10.32 | 9.50 | 8.80 | 8.20 | 7.68 |

## 7.2 Cost Drivers

In general, reported water costs are low in many regions of the U.S. These cost figures are based on operating expenditures, and generally do not include long-term maintenance costs for water infrastructure assets. Low unit costs for water have contributed to a largely reactive approach to addressing water main leaks and breaks among supply system operators. However, system operators are increasing prices to reflect the actual costs to maintain and upgrade their aging water distributions systems. The value of water in drought prone areas and the cost of water are

the primary drivers for the implementation of leak detection technologies as the benefits of leak detection are driven by the loss prevention achieved.

Water costs vary considerably nationwide depending on climate, water quality, available supply, and local demand considerations. Table 7-6 shows typical water costs from a survey of 50 U.S. cities for a customer using 15 $m^3$/month or 3,963 gal/month (Global Water Intelligence [GWI], 2014). On a unit basis, the average water cost ranges from $1.59/kgal to $9.71/kgal and averages $5.01/kgal nationwide. The water cost at the ERDC facility of $2.80/kgal is moderate compared to these nationwide values and compared to other DoD installations located in more drought-prone regions. For example, unit water costs at NAVFAC Southwest Naval Base San Diego are $14.82/kgal. The fact that a high SIR value is returned for a DoD installation with a moderate water rate and with a very conservative assumption of 13 million gallons of water lost per year suggests that the widespread application of these technologies would be beneficial.

**Table 7-7. Regional Water Rates**

| ***Location*** | **Unit Water Rate**[a] |
|---|---|
| *San Diego* | $9.71/kgal |
| *Miami* | $1.59/kgal |
| *Average of all 50 Cities* | $5.01/kgal |
| ***ERDC*** | **$2.80/kgal** |
| ***Naval Base San Diego*** | **$14.82/kgal** [b] |

(a) Calculated from GWI, 2014
(b) From FY 2016 Navy Working Capital Fund Stabilized Rates

Energy and labor costs also serve as cost drivers and vary considerably based on region. The electrical costs used in the economic analysis at ERDC is $0.08 per kW-hr and $0.14 per kW-hr (average commercial rate) for San Diego. Based on data from the Bureau of Labor Statistics (2015), the labor rate for plumbers and pipefitters nationwide ranges from $14.27 to $43.13 per hour with the median hourly wage at $26.49 per hour. Under the Davis-Bacon Act for federally-funded projects, contractors are expected to pay their laborers no less than the prevailing wage plus fringe benefits. For ERDC in Vicksburg, MS, the Davis-Bacon Act wage rate of $20.06 per hour is approximately 24% below the national average for plumbers cited by the Bureau. However, the Davis-Bacon Act wage rate at $50.37 per hour in San Diego was 17% higher than the 90th percentile labor rate of $43.13 per hour for plumbers according to the Bureau. Because of this wide variation in water and labor rates nationwide, SIR assessment was limited to two regions with the different water and labor rates as discussed below.

## 7.3 Cost Comparison

Table 7-7 compares the NPV and SIR for the three innovative acoustic sensor technologies for a moderate water cost scenario at ERDC in Vicksburg, MS to a high water cost scenario at Naval Base San Diego, CA. The comparison illustrates the impact or sensitivity of water and labor rates

on the SIR values. The NPV and SIR results for these scenarios were derived using the existing water rate at ERDC of $2.80/kgal and the water rate at Naval Base San Diego of $14.82/kgal.

**Table 7-8. NPV and SIR Estimates Using Moderate and High Regional Water Costs**

| Technology | NPV Technology Investment Cost Over 15 Years | Volume of Water Saved (Mgal) | NPV Savings with ERDC Water Rate | SIR with ERDC Water Rate | SIR = 1.0 Breakeven Labor Rate ($/hr) |
|---|---|---|---|---|---|
| ZoneScan Alpha | $250K | 194[a] | $415K | 1.66 | $58.00 |
| LeakFinderRT | $673K | 146[b] | $305K | 0.45 | NA/Service |
| Correlux | $145K | 146[b] | $305K | 2.10 | NA/Service |

| Technology | NPV Technology Investment Cost Over 15 Years | Volume of Water Saved (Mgal) | NPV Savings with San Diego Water Rate | SIR with San Diego Water Rate | SIR = 1.0 Breakeven Labor Rate ($/hr) |
|---|---|---|---|---|---|
| ZoneScan Alpha | $382K | 194[a] | $2.15M | 5.63 | $457.00 |
| LeakFinderRT | $673K | 146[b] | $1.58M | 2.35 | NA/Service |
| Correlux | $145K | 146[b] | $1.58M | 10.88 | NA/Service |

a) Estimated based on continuous daily monitoring
b) Estimated based on period inspections every 3 years

Likewise, the electrical rates were varied based on region-specific values as discussed above, while all other variables were held constant. To be consistent with prior calculations, the Davis-Bacon prevailing wage rates (plus fringe) of $20.06 per hour for Vicksburg, MS and $50.37 per hour for San Diego, CA were used. These values are comparable to the 2015 Bureau of Labor Statistics data cited above.

Table 7-8 also includes an estimated breakeven point at which the SIR value would equal one for the ZoneScan Alpha continuous monitoring technology. Given the moderate water rate at ERDC, the labor cost could more than double and the technology could still achieve a SIR value of 1.0 based on the projection. The estimated breakeven labor rate of $58.00 per hour for ERDC is well above the median labor rate of $26.49 per hour for plumbers based on the Bureau of Labor Statistics (2015). For San Diego, the ZoneScan Alpha technology is even more cost-effective achieving a SIR value of 5.63 at the $50.37 per hour prevailing wage rate for plumbers. Based on the projected breakeven labor rate analysis, the labor rate could increase over nine times and the technology would still achieve a SIR value of 1.0 at the given water rate of $14.82/kgal. Therefore, the sensitivity analysis has demonstrated that the continuous monitoring technology is likely to be cost-effective under a wide range of water and labor rates. The other two periodic inspection technologies (LeakFinderRT and Correlux) were services for a fixed daily inspection fee, so the unit labor rates are not applicable to hourly rate sensitivity analysis. However, the Correlux technology was found to be cost-effective under both moderate and high water rate scenarios with SIR values ranging from 2.10 to 10.88. The LeakFinderRT technology was found to be cost-effective under the high water cost scenario for San Diego.

.

# 8.0 IMPLEMENTATION ISSUES

This section provides information to aid in the future implementation of the technology including lessons learned as part of the demonstration and other key considerations related to technology performance.

## 8.1 DoD Need

EO 13693 requires the DoD to achieve a 36% reduction in water use by the year 2025 starting from baseline year 2007. A key element of achieving this goal will be reducing water losses from existing water distribution systems, many of which have components that have reached or exceeded their expected service life. A typical installation may have over 50 miles of potable water pipelines within its boundaries that vary in age, material, size and condition. Water loss through older pipes is often significant, and repair and replacement are urgently needed. At a frequency of 0.25 breaks per mile per year, 13 leaks per year would be typical at larger bases (WaterRF, 2015). Replacement of aging distribution system elements is a desirable outcome, but the expense can be great. Alternatively, finding and repairing the leaks will reduce water loss and avoid undermining other critical above grade infrastructure (e.g., roadways). Accurate and cost-effective technologies to pinpoint those leaks in underground piping, particularly leaks that have no visible surface expression, will substantially reduce water loss. This will also reduce costs, safeguard public health, and help to meet the EO water reduction requirement.

In addition to EO 13693, the Department of the Army revised Army Regulation AR-420-1, Army Facilities Management on 24 August 2012 to increase maintenance and inspection of building systems that impact water and energy consumption. Policy on the responsibility for attainment of installation water goals, including leak detection for installation water systems, has also been provided in a memorandum from the Assistant Secretary of the Army for Installations, Energy and Environment, dated 20 December 2012 (Hammack, 2012).

## 8.2 Technology Implementation

### 8.2.1 Intermittent Inspection

Leak detection systems that rely on an intermittent inspection approach hold the most promise for implementation at military installations at this time. This approach requires periodic surveys to be conducted at multiple locations to provide geographic coverage of an installation’s distribution system. A widely accepted best management practice with this technology is to cover an entire base every 3 to 5 years (AWWA, 2009). Both the LeakFinderRT and Correlux leak detection systems process the leak signature data in the field without any requirement for information technology (IT) security, or connection to government IT assets or the Internet. Leak detection using these systems can be procured as a service via a maintenance or job order contract. In addition, if an installation has the manpower, equipment can be procured for in-house use. (Note that the LeakFinderRT system would require IT approval for laptop computer use). The major downside to this intermittent inspection approach is that non-exposed leaks can go on for a significant period of time before detection. For example, water from a major underground leak may travel along the path of least resistance to a cracked sewer line with no

surface expression. Still, periodic surveys would also result in water savings, but with less effectiveness than a continuous monitoring approach.

Since the Correlux technology met all of the performance thresholds for the test bed evaluations, this technology could be considered for additional field testing and deployment in its current state. It is recommended that further evaluation under field conditions be undertaken at installations that would benefit the most from aggressively controlling water losses. This includes installations where water sources are constrained or supplied by providers at significant cost and/or where breaks are more likely to occur on a frequent basis because of the age and condition of installation infrastructure and site conditions such as corrosive soils.

### 8.2.2 Continuous Monitoring

Further development and investment would be required for widespread adoption of a continuous monitoring system at military installations. Continuous monitoring could be focused at older installations or in older or more problematic portions of the water distribution system (such as areas suffering from settling). Continuous monitoring systems have recently been used at numerous municipalities outside the military with reported success. However, software compatibility issues and the difficulties of securing IT approval would deter implementation at military installations under the current IT security environment. The primary operating concern to be addressed includes network security for information systems that are being deployed in conjunction with AMI systems. This concern prevented any field testing of the monitoring technologies that relied upon AMI infrastructure for data transmission by leak detection monitoring systems. This would be most problematic to address for the ZoneScan Alpha system, as this technology requires data to be transmitted to a corporate server now located in Europe for processing, and relaying of monitoring results back to the leak detection system users via the Internet.

The estimated cost of procuring and operating a US-based server for this specific technology was quoted at approximately $75,000. This is considered cost prohibitive for a single installation, but could be manageable if the cost for a centralized server was pooled across many DoD installations. In addition, based on limited research of similar leak detection systems, companies are now developing continuous monitoring systems that would not rely on Internet access and acquisition of out-of-country server technology for operation at an installation. This could potentially improve the chance of securing IT approval at DoD installations. Continuous monitoring systems hold significant long-term promise for reducing water loss as leaks can be detected near real-time allowing for repair in a shorter time frame. Competition in this emerging niche may drive down costs to a more feasible level in the near future.

## 8.3 Guidance Documents and Sustainability Initiative

The *AWWA Manual M36: Water Audits and Loss Control Programs* provides specific guidance for conducting water audits (AWWA, 2009). Procedures for identifying water losses must account for procedural errors, unauthorized connections, known and undetected leaks. Contracts for audit services should follow guidance from the most recent audit manual. For in-house services, base repair crews should be thoroughly familiar with established procedures.

The Army ERDC's Construction Engineer Research Laboratory (CERL) is currently developing a tri-service methodology known as the Sustainability Management System that will provide a computer modeling platform to track all military assets, including potable water systems to manage lifecycle repair, degradation assessment, and maintenance. A complete geographic information system inventory of leak detection data should be integrated into the model input.

No Federal regulatory requirements must be met by leak detection systems, as water supply systems are regulated primarily for water quality. Some states have passed regulations on allowable leakage levels within water distribution systems. For example, New Hampshire, New Jersey, and Washington require water utilities to implement leak detection if their water losses exceed certain threshold values (AWE, 2012). State efforts related to water conservation are expected to accelerate over time.

## 8.4 Lessons Learned

### 8.4.1 Accurate Drawings

Leak detection operators must have a good understanding of their equipment, correlator requirements and have quality drawings to work from. The layout drawings should show location of pipe segments (with lengths), valves, hydrants, directional transitions, pipe type transitions, size and location of all pipe laterals. The correlator output quality is highly dependent on entering accurate length measurements, pipeline material, and size. In many cases, pipelines are not laid out in straight lines and consequently must be addressed differently when entering data into the correlator, in cases where accurate drawings are not available. Operators unfamiliar with the pipe distribution system may have problems pinpointing a leak if provided with marginal quality drawings or there are laterals not identified on the drawings.

To demonstrate the potential issue with laterals, leaks of varying sizes were installed on a PVC lateral approximately 10 feet offset from the mainline. Test results showed that each of the technologies can detect the simulated leaks, but the correlator generally pinpointed the leak location near the intersection point on the mainline and the lateral. In a field application, where lateral locations are not exactly known, field verification of the identified leak with a ground microphone is essential.

### 8.4.2 First Test Bed Trials

The first trials conducted at the ERDC Test Bed revealed that bracketing two types of pipelines (DI and PVC) to find artificial leaks was problematic. In over 50 percent of the trials, the accuracy of the correlated leaks was outside the established limits. The experienced Echologics crew believed that because the distance between the sensors was well within the limitation of the technology (i.e., less than 200 feet) that the technology would be able to accurately pinpoint the established leaks. This turned out not to be the case and the second set of trials which bracketed only one type of material generated more accurate results. This indicates that transitions from one type of pipe material to another may be problematic for leak detection location calculations using data from acoustic sensors. The test bed trials also showed inaccurate leak location results when multiple leaks (e.g. two or more leaks) were located within the interval between sensors.

### 8.4.3 Information Network Security and Compatibility

As stated in Section 1.0, the planned evaluation of the continuous monitoring technology at an installation with an AMI system for water metering could not be performed. The primary barriers preventing the planned demonstration at JBPHH and other sites were:

- AMI systems for water were still in the process of being installed and/or not yet fully functional at some bases considered for the study including JBPHH.
- Compatibility issues existed between the DOD-managed AMI hardware and software and the continuous monitoring leak detection software systems. Although, customization was possible to adapt to different AMI brands, it was beyond the scope of the project.
- Compatible water AMI systems were identified at several privatized housing units located on DoD installations including JBPHH. However, approval could not be obtained from the private companies to participate in the field demonstration.

Although the continuous monitoring leak detection technology evaluated in this project was compatible with the AMI hardware and data transmission software at the privatized area of JBPHH and several other DoD sites, the study team was unable to get approval from the privatized utilities managers to integrate continuous monitoring leak detection with their AMI system based on prior IT contractual requirements. Future efforts at development or deployment of continuous leak detection monitoring systems at DoD locations with AMI systems should include resources for resolution of technology compatibility and security issues, as well as a review of AMI software and hardware variability across the DoD. One possible approach would be to solicit firms with demonstrated experience in integrating software and data transmission hardware from multiple vendors through federal "sources sought" notices published on the Commerce Business Daily and FedBizOpps web sites. In retrospect, it would have been prudent from a demonstration perspective to use ERDC as the host site, as their charter is uniquely positioned to serve as a site for validating technologies. Approval may have been more forthcoming for integration with an AMI system. Unfortunately, the AMI infrastructure was not yet in place at ERDC during the execution of the project. However, ERDC is currently implementing AMI in its pipe network and a future study could include integrating it with continuous leak monitoring technologies.

## 8.5 Other Observations

In the field demonstration at ERDC, a known leak was identified with evidence of significant water flow on the surface. The field test excavation revealed that the leak was under the slab of a building. Further research and development is needed to address location of leaks that may be underneath building slabs or other surface features. In an actual field application, the lateral and leak may be under a building.

## 8.6 Performance of the Technologies

This study has evaluated three technologies for leak detection that can be deployed on existing water distribution systems. The ZoneScan Alpha system is deployed to monitor infrastructure over time, while both the LeakFinderRT and the Correlux technologies are used to conduct periodic surveys by deploying the systems in the field to gather data on specific reaches of the

piping in a distribution system. The periodic approach requires the field surveys to be conducted at multiple locations in order to provide geographic coverage of an installation's distribution system. Only the Correlux technology met all of the established performance measures for the test bed evaluations. Insufficient leaks were observed during the field evaluation conducted at ERDC to assess the performance measures of any of these technologies under field conditions.

While the ZoneScan Alpha technology provides some operational advantages by providing monitoring over time, additional investigation would be required to determine whether suitable performance can be obtained from monitoring systems as currently offered, or whether further technological development is required to justify deployment at DoD installations.

Benefits of the systems will also require further evaluation under field conditions. More data are needed on the net costs of the systems, including contractor services or additional labor provided by installation staff. Similarly, more operational experience is needed to assess cost savings for installations that would be realized through decreased water losses and operational efficiencies in proactively locating and addressing leaks identified through a continuous monitoring technology. However, given the data on hand, conservative estimates indicate high SIR values for these acoustic leak detection technologies, which would make their more widespread application beneficial.

## 8.7 Future Use of the Test Bed Facility

The test bed facility at ERDC-Vicksburg is located in a relatively isolated portion of the research station. It is probable that the area will be not be disturbed for 5 to 10 years, and perhaps longer. This facility will therefore remain available for further pipe testing in the immediate future. These experiments could include testing of new leak detection equipment. However, a natural progression would investigate in situ means of pipe repair. The pipe gallery could also be used to test water security issues, such as conditions that promote lead corrosion or addressing pipes contaminated in a chemical release. Currently, land surrounding the test bed gallery is unoccupied and the test bed could be expanded to accommodate new projects.

## 9.0 REFERENCES


Alliance for Water Efficiency (AWE). 2012. *The Water Efficiency and Conservation State Scorecard: An Assessment of Laws and Policies*. April, 103 pp.

American Water Works Association (AWWA). 2009. *Manual M36: Water Audits and Loss Control Programs*. Second edition, AWWA, Denver, CO, 313 pp.

Anguiano, G., E. Chiang, V.F. Medina, S.A. Waisner, J.C. Matthews, and R. Stowe. 2015. Demonstration and Evaluation of Innovative Acoustic Leak Detection Methods for the U.S. Military. Conference: North American Society for Trenchless Technology (NASTT) 2015 No-Dig Show. Denver, CO.

Army Regulation 420-1. Facilities Engineering: Army Facilities Management. 24 August 2012.

Environmental Protection Agency (EPA). 2012. *Water Efficiency Strategies*. Available at: https://owpubauthor.epa.gov/infrastructure/sustain/wec_wp.cfm.

Fanner, P., R. Sturm, J. Thornton, R. Liemberger, S. Davis, and T. Hoogerwerf. 2007. *Leakage Management Technologies*. American Water Works Associate Research Fund Project No. 2928, Denver, CO, 380 pp.

FEMP. 2010. Annual Report to congress on Federal Government Energy Management and Conservation Programs: Fiscal Year 2007 FEMP, January 2010

Global Water Intelligence (GWI). 2014. *Global Water Market 2014 Meeting the World's Water and Wastewater Needs Until 2018.* Oxford, UK, GWI.

Grigg, N.S. 2007. Main Break Prediction, Prevention, and Control. Denver, Colorado: AWWA Research Foundation.

Hammack, Katherine. 2012. Department of the Army, Undersecretary of the Army (Installations, Energy and Environment) Memorandum: Water Goal Attainment Responsibility Policy for Installations

Hughes, D., J. Oxenford, and R. Titus. 2014. Pipe Location and Leakage Management for Small Water Systems. Water Research Foundation Web Report #4144. Denver, CO, 40 pp. Available at: http://www.waterrf.org/publicreportlibrary/4144.pdf.

Hunaidi, O. 2000. Detecting Leaks in Water-Distribution Pipes. NRC-CNRC Construction Technology Update No. 40. Institute for Research in Construction, Ottawa, Canada. October, 6 pp. Available at: https://www.nrc-cnrc.gc.ca/ctu-sc/files/doc/ctu-sc/ctu-n40_eng.pdf.

King, Tony. 2014. Personal Communication from ERDC DPW.

King, Tony. 2015. Personal Communication from ERDC DPW.

Liu, Z., Y. Kleiner, B. Rajani, L. Wang, and W. Condit. 2012. *Condition Assessment Technologies for Water Transmission and Distribution Systems*. EPA/600/R-12/017, Cincinnati, OH, March, 149 pp.

Medina, V., S. Waisner, J. Johnson, R. Wade, and J. Mattei-Sosa. 2012. Laboratory Study for Evaluating Performance of Unit Processes to Treat the Electrodialysis Reversal (EDR) Reject Stream for the Proposed Fort Irwin Water Treatment Plant. U.S. Army Engineer Research & Development Center Report. ERDC/EL TR-12-30. Available at: http://acwc.sdp.sirsi.net/client/search/asset/1013680.

National Institute of Standards and Technology (NIST). 2015. Annual Supplement to NIST Handbook 135: Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis. NISTIR 85-3273-30. Available at: http://energy.gov/sites/prod/files/2015/06/f23/ashb15.pdf.

Pacific Northwest National Laboratory (PNNL). 2013a. Army Net Zero Water Balance and Roadmap Programmatic Summary. October, 56 pp. Available at http://www.asaie.army.mil/Public/ES/netzero/docs/NZW%20Programmatic%20Summary-FINAL-10-30-13.pdf.

PNNL. 2013b. Fort Buchanan Net Zero Water Program Water Balance Report. Prepared by PNNL for the U.S. Army, Deputy Assistant Secretary of the Army for Energy and Sustainability, Washington, D.C., September, 94 pp.

Scholze, R., M. Case, L. Curvey, C. Wilson, and M. Ginsberg. 2012. "Net Zero Water Modeling Program and the Army." *AWWA ACE*, Dallas, TX, June.

WaterRF. 2015. Knowledge Management Portal on Asset Management Breaks & Leaks FAQs. Available at: http://www.waterrf.org/knowledge/asset-management/breaks-leaks/Pages/faqs.aspx.

# Appendix A
# Flow Meter Verification Data

| Trial Number (#) | Target Flow Rate (gpm) | Date | Elapsed Time (sec) | Inst. Pipeline Flow Rate (gpm) | Average Flow Rate from Flow Meter (gpm) | Total Volume Collected (gal) | Average Flow Rate (gpm) | Relative Percent Difference (RPD) (%) | RPD ≤ 5%? (Y/N) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 10 gpm | 07/29/15 | 10 | 9.83 | 9.87 | 15 | 10.34 | 4.8% | Yes |
| | | | 20 | 9.81 | | | | | |
| | | | 50 | 9.96 | | | | | |
| | | | 70 | 9.93 | | | | | |
| | | | 87 | 9.82 | | | | | |
| 2 | 5 gpm | 07/29/15 | 10 | 4.78 | 4.74 | 15 | 4.95 | 4.3% | Yes |
| | | | 30 | 4.79 | | | | | |
| | | | 45 | 4.75 | | | | | |
| | | | 60 | 4.78 | | | | | |
| | | | 80 | 4.66 | | | | | |
| | | | 100 | 4.69 | | | | | |
| | | | 120 | 4.71 | | | | | |
| | | | 140 | 4.69 | | | | | |
| | | | 160 | 4.78 | | | | | |
| | | | 182 | 4.77 | | | | | |
| 3 | 1 gpm | 07/29/15 | 10 | 1.54 | 1.53 | 5 | 1.59 | 3.7% | Yes |
| | | | 30 | 1.53 | | | | | |
| | | | 50 | 1.54 | | | | | |
| | | | 70 | 1.52 | | | | | |
| | | | 90 | 1.53 | | | | | |
| | | | 110 | 1.54 | | | | | |
| | | | 130 | 1.56 | | | | | |
| | | | 150 | 1.52 | | | | | |
| | | | 170 | 1.53 | | | | | |
| | | | 189 | 1.50 | | | | | |

# Appendix B
# Leak Flow Verification Data

| Leak No. | Date | Start Time [hh:mm] | Orifice Plate Size [in] | Area (A) of Orifice [$in^2$] | Pipeline Pressure (P)[psi] | Video Duration [sec] | Weighted-Average Flow Rate from Flow Meter [gpm] | Calculated Orifice Flow Rate (Q) by Eqn. [gpm]* | Relative Percent Difference of Flow Rate [%]** | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 07/29/15 | 2:08 PM | – | – | 89 | 60 | 0.26 | – | – | |
| 1 | 07/29/15 | 2:23 PM | 0.187 | 0.0275 | 72 | 60 | 5.92 | 7.1 | 20% | |
| 2 | 07/29/15 | 2:30 PM | 0.154 | 0.0186 | 82 | 60 | 4.07 | 5.1 | 26% | |
| 3 | 07/29/15 | 2:40 PM | 0.067 | 0.0035 | 90 | 72 | 0.79 | 1.0 | 29% | |
| 3-1 | 07/30/15 | 9:08 AM | 0.067 | 0.0035 | 90 | 60 | 0.79 | 1.0 | 29% | Redo; left leak on overnight from 07/29 to 07/30 |
| 4 | 07/29/15 | 2:49 PM | 0.125 | 0.0123 | 92 | 61 | 0.92 | 3.6 | 289% | Unknown cause for low flow; possibly obstructed. Leak detectable in April 2015 by all technologies. |
| 5 | 07/29/15 | 2:57 PM | 0.032 | 0.0008 | 90 | 99 | 0.40 | 0.2 | -42% | |
| 5-1 | 07/30/15 | 9:20 AM | 0.032 | 0.0008 | 91 | 60 | 0.40 | 0.2 | -42% | |
| 6 | 07/29/15 | 3:07 PM | 0.067 | 0.0035 | 90 | 61 | 0.49 | 1.0 | 107% | Lateral position; Orifice was later found to be obstructed by Teflon tape fragment. |
| 6-1 | 07/30/15 | 9:24 AM | 0.067 | 0.0035 | 90 | 60 | 0.39 | 1.0 | 161% | Lateral position; Orifice was later found to be obstructed by Teflon tape fragment. |
| 7 | 07/29/15 | 3:18 PM | 0.032 | 0.0008 | 92 | 129 | 0.18 | 0.2 | 30% | |
| 7-1 | 07/30/15 | 9:28 AM | 0.032 | 0.0008 | 90 | 61 | 0.37 | 0.2 | -37% | |
| 8 | 07/29/15 | 3:32 PM | 0.067 | 0.0035 | 92 | 61 | 0.64 | 1.0 | 61% | |

| Leak No. | Date | Start Time [hh:mm] | Orifice Plate Size [in] | Area (A) of Orifice [$in^2$] | Pipeline Pressure (P)[psi] | Video Duration [sec] | Weighted-Average Flow Rate from Flow Meter [gpm] | Calculated Orifice Flow Rate (Q) by Eqn. [gpm]* | Relative Percent Difference of Flow Rate [%]** | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| 8-1 | 07/30/15 | 9:31 AM | 0.067 | 0.0035 | 90 | 60 | 0.72 | 1.0 | 41% | |
| 9 | 07/29/15 | 3:36 PM | 0.125 | 0.0123 | 89 | 99 | 2.80 | 3.5 | 26% | |
| 10 | 07/29/15 | 3:40 PM | 0.154 | 0.0186 | 82 | 61 | 4.03 | 5.1 | 27% | |
| 11 | 07/29/15 | 3:51 PM | 0.187 | 0.0275 | 92 | 67 | 6.17 | 8.0 | 30% | |
| 11-1 | 07/30/15 | 8:33 AM | 0.187 | 0.0275 | 64 | 60 | 5.60 | 6.7 | 19% | |